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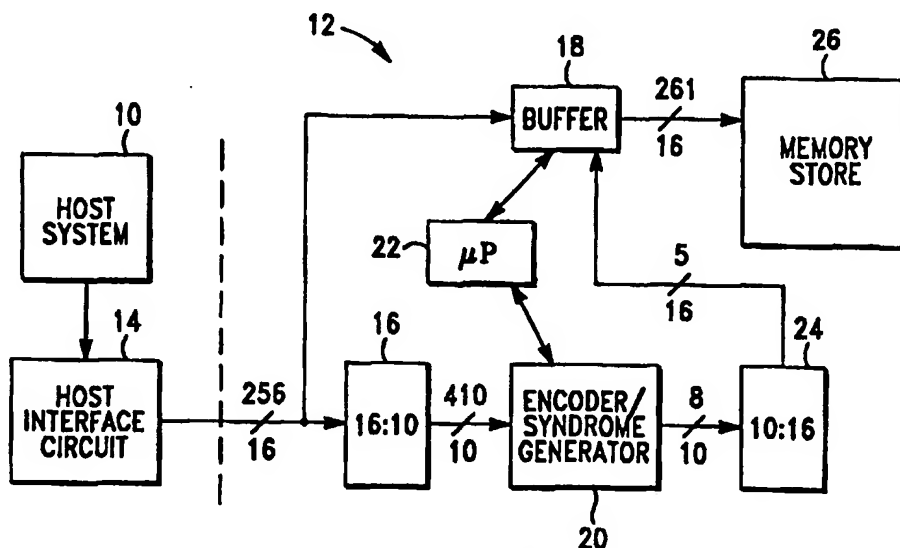
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(54) Title: DEDICATED ALU ARCHITECTURE FOR 10-BIT REED-SOLOMON ERROR CORRECTION MODULE

(57) Abstract

A system architecture for implementing a 10-bit Reed-Solomon code for detecting and correcting data errors in a single code word to protect a data block containing up to 1023 10-bit data symbols, i.e., the equivalent of up to 1278 8-bit symbols, including error check redundancy, maximizes the use of all allocated error correction overhead for an entire block of data, regardless of the particular error pattern characteristics encountered in a given system application. The architecture is particularly

well suited for digital data processing and/or storage systems encountering non-bursty, (i.e., substantially random), error patterns, such as characteristic of data storage and retrieval systems employing semiconductor based memory stores. 5-bit extension field operations, (i.e., over a Galois field GF(2)), generated by using the irreducible polynomial $P(x) = x^5 + x + 1$, over GF(2), are utilized to perform certain, requisite arithmetic functions over the Galois field GF(2) with a hardware-minimized error correction architecture.



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**DEDICATED ALU ARCHITECTURE FOR 10-BIT REED-SOLOMON
ERROR CORRECTION MODULE**

Field of the Invention

This invention pertains to the field of error correction in digital data processing and storage systems and, more particularly, to methods and apparatus for employing a 10-bit Reed-Solomon code for the detection and correction of digital data errors within a block of data being transmitted between elements of a data processing and/or storage system.

Background of the Invention

Error correction techniques and architectures are well known in digital data processing and communications systems, including systems having data storage subsystems such as magnetic, optical, or semiconductor based memory stores. Detection and, where possible, correction of erroneous data has been achieved by using an encoder circuit to construct some number of "redundant" m-bit error check symbols, which mathematically characterize the information in a selected block of data. The error check symbols are then appended to the data block and transferred or stored therewith. When the data block is received, or later retrieved from memory, the accuracy of the data can be evaluated by use of these appended error check symbols. For example, one methodology is to repeat the encoding process on the received or retrieved

block of data, often using the same encoder, and then compare the newly derived error check symbols with those previously appended to the data block. If the newly derived error check symbols are identical to those appended to the data block, the information contained in the received data block is presumed to be error free; if not, "error syndrome" information is generated from the difference between the newly derived and originally appended error check symbols, which, depending upon the nature and amount of the error check information, can be used to locate the error(s) within the data block and determine the correct data values for substitution therefor.

The use of Reed-Solomon codes has become a prevalent methodology for performing error detection and correction in digital communications, processing and storage applications. In a Reed-Solomon code, sequential m-bit data symbols forming a data block are treated as being representative of coefficients of a polynomial in a variable, e.g., "x". In particular, a sequence of k m-bit data "message" symbols $\{m_0, m_1, m_2, \dots, m_{k-1}\}$ are treated as a "message polynomial," $m(x)$, of degree k-1, where

$$m(x) = m_0x^{k-1} + m_1x^{k-2} + \dots + m_{k-2}x + m_{k-1},$$

An encoder divides the message polynomial, $m(x)$, by a selected "generator polynomial," $g(x)$, to produce a "remainder polynomial," $r(x)$, having coefficients in the form of r m-bit error check symbols.

A Reed-Solomon generator polynomial, $g(x)$, has the general form:

$$g(x) = \prod_{i=0}^{r-1} (x - \alpha^{J_0 + i})$$

where α ("alpha") is a primitive element of a Galois field, $GF(q)$, whose $q-1$ powers, $\{\alpha^0, \alpha^1, \alpha^2, \dots, \alpha^{q-2}\}$, exhaust the non-zero elements of the field and where J_0 is some arbitrary logarithm base α of the first root of the generator polynomial. Usually, in binary systems, q is a power of 2, i.e., $q = 2^m$, for some m . For example, where $r = 4$, -- i.e., where four redundant error check symbols are to be generated --, the generator polynomial may be expressed in the factored form:

$$g(x) = (x - \alpha^{J_0})(x - \alpha^{J_0+1})(x - \alpha^{J_0+2})(x - \alpha^{J_0+3}).$$

As can be seen, the nature of the generator polynomial, $g(x)$, determines, among other things, the extent and complexity of the error correction code. In particular, the degree of the generator polynomial determines the number (r) of error check symbols contained in the remainder polynomial, $r(x)$. However, the greater the degree of the polynomial that is selected for the generator polynomial, the more complex the associated encoder circuitry must be to perform the necessary computations.

Generally, the error check symbols are appended to the message

symbols to form a Reed-Solomon "code word" of length $n = k + r$ m-bit symbols, where the message and error check symbols are elements in the finite Galois field $GF(2^m)$. This is referred to as an "n-symbol codeword," consisting of "m-bit symbols," or as an example of an "m-bit Reed-Solomon implementation." By definition, each
 5 code word, when considered as a polynomial, $c(x)$, of degree $n-1$, where

$$c(x) = c_0x^{n-1} + c_1x^{n-2} + \dots + c_{n-2}x + c_{n-1},$$

is evenly divisible by the generator polynomial, $g(x)$. In other
 10 words, $c(x) \bmod g(x) = 0$. Since a correctly received code word, $c'(x)$, will also be evenly divisible by $g(x)$, one well known procedure for detecting errors upon receipt or retrieval of a code word, $c'(x)$, is to divide it by $g(x)$. If $c'(x) \bmod g(x)$ is zero, then $c'(x)$ is presumed to have been correctly received. If the
 15 remainder of $c'(x)/g(x)$ is non-zero, then one or more errors have occurred and an error correction routine is invoked by calculating r m-bit "error syndromes," S_0, \dots, S_{r-1} , respectively, (i.e., "symptoms of error"), from the non-zero remainder of $c'(x)/g(x)$.

Several procedures are known for computing the error locations
 20 and proper values from the calculated error syndromes. These techniques involve error-locator-polynomial determination, root finding for determining the positions of the errors, and error value determination for determining the correct bit-pattern of the errors. In many error detection and correction architectures, the

block of data being evaluated is temporarily stored in a buffer memory, while the error correction procedure is performed with the error syndromes generated from the received, or retrieved, code word. Known architectures may perform the error correction routines by using hardware circuitry under the control of a programmed state machine or arithmetic logic unit, by using a microprocessor under firmware control, or by some combination of both. For example, several known architectures perform the correction of a very small number of errors, typically no more than one or two, by hardware circuitry "on-the-fly," i.e., without stopping or substantially slowing the bit-rate of the data blocks during a typical transfer, or retrieval, of multiple blocks of data. The correction of more than these one or two errors, if enabled by sufficient error syndrome information, is typically given to a system level microprocessor to carry out the error correction operations on an as-needed, or "interrupt" basis, i.e., where the data flow is temporarily slowed, or stopped. When this happens, the microprocessor is fed the error correction syndrome information for a data block having the more than one or two errors and calculates values for locating and correcting all of the errors under direction of error correction firmware. In the event the data is not correctable, i.e., where there are more errors detected in the block than can be corrected by the hardware and/or firmware error correction architecture, an error recovery procedure may be

attempted, e.g., which may involve one or more retries to recover data from the storage media.

One general limitation of Reed-Solomon codes is that the maximum number of m-bit data symbols that can be corrected within an m-bit code word is limited to the integer portion, or "floor," of the number of appended error check symbols (r) divided by two, i.e., $\text{INT}(r/2)$. Another general limitation is that each m-bit code word is limited to a maximum length of $2^m - 1$ symbols, sometimes referred to as its "natural block length," including both the source data symbols and the appended error check symbols. Thus, implementations of Reed-Solomon error correction techniques must take into account these limitations.

For example, commonly owned U.S. Patent No. 5,241,546, issued to Peterson et al., discloses a system architecture which employs a Reed-Solomon code to detect and correct data errors in a disk drive data storage system which handles data in blocks, or "sectors," containing 512 8-bit symbols (or "bytes"), $d[1]$, $d[2]$, . . . , $d[512]$, respectively. Because the total number of 8-bit symbols that can be protected in a single 8-bit code word is $2^8 - 1 = 255$ symbols, each 512 byte data sector is divided into smaller blocks for purposes of performing error correction. In so doing, the Peterson et al. Patent also takes into account that data errors encountered in certain digital data communication and storage systems, such as in magnetic based disk drive systems, are often

"bursty" in nature, i.e., the data errors tend to appear across consecutive bit positions within a block of data, as opposed to occurring randomly. The 512 data bytes are therefore serially divided into three separate "interleaves," each interleave
5 containing every third data byte, -- i.e., with interleave 1 containing data bytes d[1], d[4], d[7], . . . , d[511], interleave 2 containing data bytes d[2], d[5], d[8], . . . , d[512], and interleave 3 containing data bytes d[3], d[6], d[9], . . . , d[510], respectively. Each interleave is then separately encoded
10 to form a corresponding 8-bit Reed-Solomon code word.

By distributing successive data bytes into separate code words for purposes of error correction, the 3-interleave architecture offers the advantage of, for example, treating the occurrence of an "error burst" of three successive corrupted data bytes as, in
15 effect, a single byte error occurring in each code word. In other words, because of the substantial likelihood that data errors, if any, will occur in consecutive data symbols, the 3-interleave architecture increases the probability that encountered symbol errors will be distributed evenly into separate code words, thereby
20 facilitating correction of a greater number of total symbol errors per data sector, without requiring additional error correction capability for a given code word.

The advantage of an interleave architecture is lost, however, if the communication, data processing, and/or storage system

application is not prone to bursty error patterns. For example, in a digital data system employing a semiconductor based memory in which error patterns occur in a substantially random manner, implementation of an interleave architecture may actually result in a substantial portion of the allocated error check redundancy being ineffective, since encountered errors are much less likely to be evenly distributed across the interleaves. Moreover, if the number of errors occurring in a single interleave exceed the error correction capability of that code word, the entire data sector may be lost, even if the total number of errors occurring sector-wide would otherwise have been within the allotted error correction capability had they been distributed evenly across all interleaves.

Thus, in a non-bursty applications it would be desirable to fully utilize all allocated error check redundancy to perform error correction for an entire data block or sector, e.g., by using of a single Reed-Solomon code word, regardless of the particular symbol size format of the data block.

Summary of the Invention

The present invention provides a Reed-Solomon error correction methodology and architecture which is suited for digital data communication, processing and/or storage systems encountering substantially random error patterns, such is characteristic of a data storage and retrieval system employing a semiconductor based memory store.

A general object of one aspect of the present invention is to provide a Reed-solomon error correction methodology and architecture ideally adapted to a mass production environment, which minimizes hardware components and the related production costs associated therewith.

A general object of another aspect of the present invention is to provide system architecture for implementing a 10-bit Reed-Solomon code for detecting and correcting data errors in a single code word to protect a data block containing up to 1023 10-bit data symbols, i.e., the equivalent of up to 1278 8-bit symbols, including error check redundancy.

A general object of yet another aspect of the present invention is to provide a Reed-Solomon error correction architecture which maximizes the use of all allocated error correction overhead for an entire block of data, regardless of the particular error pattern characteristics encountered in a given system application.

A general object of yet another aspect of the present invention is to provide a practical implementation of a 10-bit Reed-Solomon error correction code by employing 5-bit extension field operations over a Galois field (2^5) to perform certain, requisite arithmetic functions with a hardware-minimized error correction architecture.

A more specific object of the hardware-minimized implementation aspect of the present invention is to provide a 10-bit Reed-Solomon error correction methodology and architecture which employs 5-bit extension field operations utilizing a Galois field $GF(2^5)$ generated from the generator polynomial $g(x) = x^5 + x^2 + 1$, over $GF(2)$.

Yet another more specific object of the hardware-minimized implementation aspect of the present invention is to provide a 10-bit Reed-Solomon error correction methodology and architecture which generates the Galois field $GF(2^{10})$ using the irreducible polynomial $P_{1024}(y) = y^2 + y + 1$, over a Galois field $GF(2^5)$ generated from the generator polynomial $g(x) = x^5 + x^2 + 1$, over $GF(2)$.

In accordance with these and other objects, features and aspects of the present invention, a data block of m -bit data symbols is formatted into a sequence of k 10-bit data symbols and passed through an encoder which constructs a preselected number r 10-bit error check symbols, where $k + r \leq 1023$. The error check symbols are converted back into an m -bit symbol format and appended

to the original m-bit data block for transport or storage. Upon being received, or later retrieved from storage, the m-bit data block, including the appended error check symbols, is again formatted as a sequence of 10-bit symbols and passed through a decoder/syndrome generator, which generates r 10-bit error syndromes. If any of the error syndromes are non-zero, thereby indicating the existence of one or more 10-bit symbol errors, the error syndromes are fed into a error correction module, which, using a Galois field arithmetic logic unit ("GF-ALU") under the control of a programmed state machine, conducts 10-bit Reed-Solomon error correction operations (i.e., over a 10-bit Galois field $GF(2^{10})$), preferably to determination the location and correct values of up to two 10-bit symbol errors by hardware solution and up to four 10-bit symbol errors under firmware control.

According to one aspect of the present invention, the GF-ALU performs certain arithmetic functions, preferably including at least the 10-bit multiplication and inversion functions, respectively, by 5-bit extension field operations over a Galois "sub field" $GF(2^5)$, generated by using the irreducible polynomial:

$$P_{32}(x) = x^5 + x^2 + 1, \text{ over } GF(2),$$

with each 5-bit nibble represented in a standard basis as a fourth degree polynomial of "x"; i.e., where a 5-bit nibble $\{d_4, d_3, d_2, d_1, d_0\}$ is represented as coefficients in the polynomial:

$$d_4x^4 + d_3x^3 + d_2x^2 + d_1x + d_0.$$

Addition of the 5-bit nibbles is preferably performed through a bit-wise XOR operation. Multiplication is preferably performed as standard polynomial multiplication, reduced modulo $P_{32}(x)$.

According to another aspect of the present invention, the
5 field $GF(2^{10})$ is generated using the irreducible polynomial:

$$P_{1024}(y) = y^2 + y + 1, \text{ over } GF(2^5),$$

with the 10 bit symbols represented in a standard basis as a sum of the powers of "y" over $GF(2^5)$, i.e., with each 10-bit symbol treated as two 5-bit nibbles (e_1, e_0), which represents $e_1y + e_0$, to perform
10 the requisite arithmetic functions. Addition of the 10-bit symbols is preferably performed through a bit-wise XOR operation. Multiplication is preferably performed as standard polynomial multiplication, reduced by modulo $P_{1024}(y)$. In one preferred embodiment, the element $\alpha = (101)_h$ (i.e., $\{0100000001\}$ binary),
15 serves as a primitive element of $GF(2^{10})$.

In this manner, 10-bit arithmetic operations are accomplished by concatenating the result of 5-bit extension field operations performed on the most significant and least significant 5-bit nibbles, respectively, of the respective 10-bit symbols.

20 These and other objects, aspects, advantages and features of the present invention will be more fully understood and appreciated by those skilled in the art upon consideration of the following detailed description of a preferred embodiment, presented in conjunction with the accompanying drawings.

Brief Description of the Drawings

It is to be understood that the accompanying drawings are provided for the purpose of illustration only, and are not intended as a definition of the limits of the invention. The drawings
5 illustrate both the design and utility of a preferred embodiment of the present invention, in which:

FIG. 1 is a functional block diagram of the host-to-memory (write) circuit of a semiconductor based data storage and retrieval system embodying aspects of the present invention;

10 FIG. 2 is a functional block diagram of the memory-to-host (read) circuit of the semiconductor based data storage and retrieval system shown in FIG. 1;

FIG. 3 is a flow chart depicting a preferred error correction process;

15 FIG. 4 is a block diagram illustrating the functional system architecture of a preferred error correction module; and

FIG. 5 is a block diagram illustrating the functional system architecture of a preferred Galois field arithmetic logic unit within the error correction module of FIG. 4.

20 Detailed Description of the Preferred Embodiment

Referring to FIG. 1, a host data processing system 10 packetizes a block of digital data for storage in an adjunct data storage and retrieval system 12. While particular blocks of data

being transported by the host system 10 to the storage system 12 may vary in size and format with differing applications and operating system architectures, for purposes of describing the illustrated preferred embodiment, a commonly used data block size is selected, which contains 256 16-bit data symbols for a total of 4096 bits. A host interface circuit 14, such as, e.g., a SCSI or IDE interface device, receives the data block from the host system 10. The interface circuit 14 then transmits the data block through a 16:10 bit wide conversion circuit 16, which serially reformats the 256 16-bit data symbols into 410 10-bit data symbols, i.e., a total of 4100 bits, with the final four bits of the 410th data symbol comprising added zeros. The data block is also transmitted by the host interface circuit 14 directly into to a holding buffer 18, without reformatting.

In alternate embodiments, the data block 12 may be packetized in varying bit formats by the host system 10 and/or host interface circuit 14. For example, the same size data block (i.e., 4096 bits) may be packetized in a "byte-size" format as 512 8-bit data symbols, or "bytes," as well. In this later case, the bit-wide conversion circuit 16 would be designed to reformat the 512 8-bit data symbols into the 410 10-bit data symbols, i.e., at an 8:10 ratio instead of a 16:10 ratio. Alternatively, the data block may be originally packetized by the host system 10 in a 10-bit symbol format, which would eliminate the need for the bit-wide conversion

circuit 16 within the data storage and handling system 12.

Whatever the original symbol bit-format of the data block, once converted into 10-bit format, the individual data symbols are transmitted through a 10-bit Reed-Solomon encoder circuit 20, which
5 generates a preferred number r of 10-bit error check symbols based on a preferred generator polynomial, $g(x)$, where r is equal to the polynomial degree of $g(x)$. For purposes of describing the illustrated preferred embodiment, wherein correction of up to two 10-bit data errors by direct hardware solution and up to four 10-
10 bit errors by firmware solution is preferred, an exemplary generator polynomial $g(x)$ of degree $r = 8$ has been selected, where (in factored form):

$$g(x) = (x + \alpha^0)(x + \alpha^1)(x + \alpha^2)(x + \alpha^3)(x + \alpha^4) * \\ *(x + \alpha^5)(x + \alpha^6)(x + \alpha^7).$$

15 While any number of known Reed-Solomon encoder circuits may be utilized to generate the error check symbols, e.g., such as an eight stage linear shift register with feedback, a combined encoder/syndrome generator circuit 20 of the type disclosed in an article entitled "A Combined Reed-Solomon Encoder and Syndrome
20 Generator with Small Hardware Complexity," by G. Fettweis and M. Hassner, p 1871-74, IEEE, 0-7803-0593-0/92 (1992), is preferably employed. An embedded system microprocessor 22 directs the combined encoder/syndrome generator circuit 20 to switch to "encode mode," wherein the encoder circuit 20 divides the 410 10-bit data

symbols of the data block by $g(x)$ to produce a "remainder" comprising 8 10-bit error check symbols.

5 The 8 error check symbols are transmitted through a 10:16 bit wide conversion circuit 24, which serially reformats the 8 10-bit error check symbols into 5 16-bit symbols. The 5 16-bit symbols are then appended to the 256 16-bit data symbols of the original data block in buffer 18, i.e., which were transmitted directly from the host interface circuit 14, the 261 16-bit symbols forming a code word. The code word is released from buffer 18 by the system
10 microprocessor 22 and is stored in a semiconductor based memory store 26, such as, e.g., a "FLASH" RAM. In alternate configurations and embodiments, the data block may be transmitted directly from the host interface circuit 14 into the memory store 26, i.e., without employing a holding buffer, with the reformatted
15 (16-bit) error check symbols appended thereto directly in the memory store 26.

Referring to FIG. 2, the 261 16-bit code word is retrieved from the semiconductor memory store 26 and transmitted into a holding buffer 28, which may be the same buffer as buffer 18. The
20 code word is also transmitted through a 16:10 bit-wide conversion circuit 30. Preferably, holding buffer 28 retains only the first 256 symbols of the code word, i.e., only the symbols comprising the original source data and not the 5 error check symbols, while all 261 symbols are passed through the 16:10 bit-wide conversion

circuit 30. The bit-wide conversion circuit 30 reformats the 261 * 16-bit code word into a 418 * 10-bit codeword, -- i.e., the 410 10-bit source data symbols, including the added four zeros in the 410th symbol, plus the 8 10-bit error check symbols.

5 The 418 10-bit symbol code word is passed through the combined encoder/syndrome generator 20, which, having been switched to "syndrome" mode by the system microprocessor 22, generates eight 10-bit error syndromes, $S_0 \dots S_7$, respectively, therefrom. Other syndrome generation circuitry may be alternatively be employed, 10 such as conventional DFT circuits, or the like. The error syndromes are evaluated in the encoder/syndrome generator 20 and, if all syndromes are determined to be zero, (i.e., 80 consecutive zero bits), the retrieved data block is presumed to be error free and the system microprocessor 22 signals the holding buffer 28 to 15 release the 256 16-bit data symbols to the host interface circuit 14. The host interface circuit 14 then transmits the data block to the host system 10 for use in its intended application.

 If, however, one or more of the 8 10-bit error syndromes is non-zero, the syndromes are supplied to an error correction module 20 36 for determination of the location and correct values of the symbol(s) in error. As depicted in the flow chart in FIG. 3, the error correction module 36 executes the "direct solution," or "Peterson Gorenstein Zierler" algorithm, for finding the location(s) and value(s) of up to two 10-bit symbol errors using a

hardware solution. If the existence of more than two errors is detected during the error correction routine, the error syndromes are transferred to the system microprocessor 22, which, under firmware control, can determine the correct locations and values of up to four 10-bit symbol errors.

Referring to FIG. 4, the error correction module 36 operates under the control of a programmed state controller 42, which directs a specialized 10-bit Galois field arithmetic logic unit 44 ("GF-ALU"), to perform the requisite addition, multiplication, inversion, squaring and table look-up operations necessary to execute the error correction algorithm depicted in FIG. 3. Eight registers, $R_0 - R_7$, 46a-h, respectively, are provided for holding interim results, with register load enables 48 (not shown in detail) provided to control which register is loaded with the result of the operation from the particular preceding instruction of the state controller 42. In the illustrated preferred embodiment, register R_0 , 46a, is a dedicated source operand for addition operations and register R_1 , 46b, is a dedicated source operand for multiplication operations, respectively. Registers R_2 , 46c, and R_3 , 46d, respectively, are used for storing the calculated error location (or "locator") values, X_0 and (if double error) X_1 , respectively. Registers R_4 , 46e, and R_5 , 46f, respectively, are used for storing the calculated error values, Y_0 and (if double error) Y_1 , respectively. It may be possible to use a different

register configuration in alternate embodiments, depending on the order of steps performed.

The following tables list the preferred state instructions given by the state controller 42 to the GF-ALU 44. Table 1 lists the state instructions for the "Double Error Decoding" process, Table 2 includes the state instructions for "Double Error Checking" process, and Table 3 includes the state instructions for "Single Error Decoding and Checking" process, respectively. In the state tables, "st_" identifies each given state; "src" identifies the "source" register or error syndrome, respectively, which contains or comprises the input data to be used in the specified operation. "Inst" refers to the particular instruction, or mathematical operation to be performed by the GF-ALU 44, where "load" calls for loading the input value into a specified register, "mult" calls for multiplying the input value with the contents of register R_1 , "sqre" calls for squaring the input value, "accm" calls for adding the input value to the contents of register R_0 , and "noop" calls for a branch to another state if a specified zero or non-zero value is determined. The "dec" entry refers to the specific register location, if any, in which the resulting value of a given state operation is to be stored. The new contents, if any, of the registers following each state operation are also included, as is a brief comment to explain, if necessary, the operation that was performed.

TABLE 1
Double Error Decoding

st_	src	inst	dec	R ₀	R ₁	R ₂	R ₃	R ₄	R ₅	R ₆	R ₇	Comment
00	S ₀	load	R ₁		S ₀							$t_0 = S_0 S_2$
01	S ₂	mult	R ₀	t ₀								$t_1 = S_1^2$
02	S ₁	sqre	R ₂			t ₁						$t_2 = S_0 S_2 + S_1^2 = \det[M_1]$
03	R ₂	accm	R ₂			t ₁						branch if zero to single solution (st_4E)
04		noop										$t_3 = S_0 S_3$
05	S ₃	mult	R ₀	t ₃	S ₁							
06	S ₁	load	R ₁									$t_4 = S_1 S_2$
07	S ₂	mult	R ₃				t ₄					$t_5 = S_0 S_3 + S_1 S_2 = \text{numerator}[\Lambda_1]$
08	R ₃	accm	R ₃				t ₅					branch if zero to decoder fails (st_66)
09		noop										$t_6 = S_1 S_3$
0a	S ₃	mult	R ₀	t ₆								$t_7 = S_2^2$
0b	S ₂	sqre	R ₄					t ₇				$t_8 = S_1 S_3 + S_2^2 = \text{numerator}[\Lambda_2]$
0c	R ₄	accm	R ₄					t ₈				branch if zero to decoder fails (st_66)
0d		noop										$t_9 = 1/\det[M_2]$
0e	R ₂	invt	R ₁		t ₉							$t_{10} = \Lambda_1$
0f	R ₃	mult	R ₃				t ₁₀					$t_{11} = \Lambda_2$
10	R ₄	mult	R ₄					t ₁₁				

st_	src	inst	dec	R ₆	R ₁	R ₂	R ₃	R ₄	R ₅	R ₆	R ₇	Comment
11	R ₃	invt	R ₁		t ₁₂							t ₁₂ = 1/Λ ₁
12	S ₁	mult	R ₇									t ₁₃ = S ₁ /Λ ₁
13	R ₁	squre	R ₁		t ₁₄							t ₁₄ = 1/Λ ₁ ²
14	R ₁₄	mult	R ₁		t ₁₅							t ₁₅ = Λ ₂ /Λ ₁ ²
15	R ₁	dbls	R ₁		t ₁₆							t ₁₆ = soln of y ² + y + Λ ₂ /Λ ₁ ² = 0, ω
16		noop										branch if zero to decoder fails (st_66)
17		mult	R ₄					t ₁₇				t ₁₇ = Λ ₁ ω = X ₀
18	R ₄	load	R ₆	t ₁₇								
19	R ₃	acem	R ₅									t ₁₈ = X ₀ + Λ ₁ = X ₁
1a	S ₀	mult	R ₆	t ₁₉								t ₁₉ = ω S ₀
1b	R ₇	acem	R ₆	t ₂₀								t ₂₀ = ω S ₀ + S ₁ /Λ ₁ = Y ₁
1c		noop										branch if zero to decoder fails (st_66)
1d	S ₀	acem	R ₅									t ₂₁ = S ₀ + Y ₁ = Y ₀
1e		noop										branch if zero to decoder fails (st_66)
1f	R ₆	load	R ₇								t ₂₀	store Y ₁

TABLE 2
Double Error Solution Checking

st_	src	inst	dec	R ₀	R ₁	R ₂	R ₃	R ₄	R ₅	R ₆	R ₇	Comment
20	R ₄	sqre	R ₁		t ₁₂	t ₁₃						t ₁₁ = X ₀ ²
21	R ₆	mult	R ₂									t ₂₃ = X ₀ ² Y ₀
22	R ₅	sqre	R ₁		t ₁₄							t ₁₄ = X ₁ ²
23	R ₇	mult	R ₃				t ₁₅					t ₁₅ = X ₁ ² Y ₁
24	R ₃	load	R ₀	t ₁₅								t ₁₆ = X ₀ ² Y ₀ + X ₁ ² Y ₁
25	R ₁	accm	R ₀	t ₁₆								t ₁₇ = S ₁ + X ₀ ² Y ₀ + X ₁ ² Y ₁
26	S ₁	accm	R ₀	t ₁₇								branch if nonzero to decoder fails
27		noop										(st_66)
28	R ₄	load	R ₁		X ₀	t ₁₈						t ₁₈ = X ₀ ³ Y ₀
29	R ₁	mult	R ₂		X ₁							t ₁₉ = X ₁ ³ Y ₁
2a	R ₅	load	R ₁									
2b	R ₃	mult	R ₃									
2c	R ₃	load	R ₀	t ₁₉			t ₁₉					t ₁₉ = X ₀ ³ Y ₀ + X ₁ ³ Y ₁
2d	R ₁	accm	R ₀	t ₁₉								t ₂₀ = S ₁ + X ₀ ³ Y ₀ + X ₁ ³ Y ₁
2e	S ₁	accm	R ₀	t ₂₀								branch if nonzero to decoder fails
2f		noop										(st_66)

Double Error Solution Checking

st_	src	inst	dec	R ₀	R ₁	R ₂	R ₃	R ₄	R ₅	R ₆	R ₇	Comment
30	R ₃	mult	R ₃				t ₃₁					t ₃₁ = X ₁ ⁴ Y ₁
31	R ₄	load	R ₁		X ₀							
32	R ₂	mult	R ₂									t ₃₃ = X ₀ ⁴ Y ₀
33	R ₃	load	R ₀									
34	R ₁	accm	R ₀	t ₃₂								t ₃₄ = X ₀ ⁴ Y ₀ + X ₁ ⁴ Y ₁
35	S ₄	accm	R ₀	t ₃₄								t ₃₅ = S ₄ + X ₀ ⁴ Y ₀ + X ₁ ⁴ Y ₁
36		noop		t ₃₅								branch if nonzero to decoder fails (st_66)
37	R ₂	mult	R ₂									t ₃₆ = X ₀ ⁵ Y ₀
38	R ₃	load	R ₁		X ₁							
39	R ₃	mult	R ₃									t ₃₇ = X ₁ ⁵ Y ₁
3a	R ₃	load	R ₀									
3b	R ₂	accm	R ₀	t ₃₇								t ₃₈ = X ₀ ⁵ Y ₀ + X ₁ ⁵ Y ₁
3c	S ₃	accm	R ₀	t ₃₈								t ₃₉ = S ₃ + X ₀ ⁵ Y ₀ + X ₁ ⁵ Y ₁
3d		noop		t ₃₉								branch if nonzero to decoder fails(st_66)
3e	R ₃	mult	R ₃									t ₄₀ = X ₁ ⁶ Y ₁
3f	R ₄	load	R ₁		X ₀							
40	R ₁	mult	R ₂									t ₄₁ = X ₀ ⁶ Y ₀
41	R ₃	load	R ₀									
42	R ₂	accm	R ₀	t ₄₀								t ₄₂ = X ₀ ⁶ Y ₀ + X ₁ ⁶ Y ₁

Double Error Solution Checking

st_	src	inst	dec	R ₀	R ₁	R ₂	R ₃	R ₄	R ₅	R ₆	R ₇	Comment
43	S ₆	accm	R ₀	t ₀								t ₀ = S ₆ + X ₀ 'Y ₀ + X ₁ 'Y ₁ branch if nonzero to decoder fails (st_66)
44		noop										
45	R ₁	mult	R ₁			t ₄						t ₄ = X ₀ 'Y ₀
46	R ₂	load	R ₁		X ₁							
47	R ₃	mult	R ₃									
48	R ₃	load	R ₀	t ₅								t ₅ = X ₁ 'Y ₁
49	R ₁	accm	R ₀	t ₆								t ₆ = X ₀ 'Y ₀ + X ₁ 'Y ₁
4a	S ₇	accm	R ₀	t ₇								t ₇ = S ₆ + X ₀ 'Y ₀ + X ₁ 'Y ₁
4b		noop										branch if nonzero to decoder fails(st_66) set status for successful double decoding
4c	R ₁	stat	R ₁									
4d		noop										branch to decoding complete (st_67)

TABLE 3
Single Error Decoding and Checking

st_	src	inst	dec	R ₀	R ₁	R ₂	R ₃	R ₄	R ₅	R ₆	R ₇	Comment
4e	S ₀	invt	R ₁		t ₄₈							t ₄₈ = 1/S ₀
4f		noop										branch if zero to decoder fails (st_66)
50	S ₁	mult	R ₁		t ₄₉							t ₄₉ = S ₁ /S ₀ = X ₀
51		noop										branch if zero to decoder fails (st_66)
52	S ₁	mult	R ₀	t ₅₀								t ₅₀ = S ₁ X ₀
53	S ₂	accm	R ₀	t ₅₁								t ₅₁ = S ₁ X ₀ + S ₂
54		noop										branch if nonzero to decoder fails (st_66)
55	S ₁	mult	R ₀	t ₅₂								t ₅₂ = S ₂ X ₀
56	S ₃	accm	R ₀	t ₅₃								t ₅₃ = S ₂ X ₀ + S ₃
57		noop										branch if nonzero to decoder fails (st_66)
58	S ₃	mult	R ₀	t ₅₄								t ₅₄ = S ₃ X ₀
59	S ₄	accm	R ₀	t ₅₅								t ₅₅ = S ₃ X ₀ + S ₄
5a		noop										branch if nonzero to decoder fails (st_66)
5b	S ₄	mult	R ₀	t ₅₆								t ₅₆ = S ₄ X ₀
5c	S ₅	accm	R ₀	t ₅₇								t ₅₇ = S ₄ X ₀ + S ₅

st_	src	inst	dec	R ₀	R ₁	R ₂	R ₃	R ₄	R ₅	R ₆	R ₇	Comment
5d		noop										branch if nonzero to decoder fails (st_66)
5e	S ₅	mult	R ₀	t ₅₈								t ₅₈ = S ₅ X ₀
5f	S ₆	accm	R ₀	t ₅₉								t ₅₉ = S ₅ X ₀ + S ₆
60		noop										branch if nonzero to decoder fails (st_66)
61	S ₆	mult	R ₀	t ₆₀								t ₆₀ = S ₆ X ₀
62	S ₇	accm	R ₀	t ₆₁								t ₆₁ = S ₆ X ₀ + S ₇
63		noop										branch if nonzero to decoder fails (st_66)
64	R ₁	stat	R ₁									set status for successful single error decoding
65		noop										noop unconditional branch to state 67
66	R ₀	stat	R ₀									set status to indicate decoder failure
67	R ₁	load	R ₄					X ₀				load X ₀ value into locator output register
68	S ₀	load	R ₆							Y ₀		load Y ₀ value into error value output register
69		noop										decoder complete - idle state

In the preferred state instructions set forth in Tables 1-3, respectively, there are a total of 106 possible instructions (or "states") to be carried out during execution of the error correction algorithm. The state controller 42 will continue serial execution of instructions, until either a double or single error solution is completed, or until both fail, with the actual number of states depending upon which event occurs. If either the double or single error decoding process is successfully completed, both the location(s) of the 10-bit symbol error(s), X_0 and (if double error) X_1 , respectively, and the correct 10-bit data value(s) for substitution therefor, Y_0 and (if double error) Y_1 , respectively, are obtained from the respective registers $R_4 - R_7$, 46e-h, by the system microprocessor 22. In the event both double and single solutions fail, the existence of more than two errors is presumed and the eight error syndromes, $S_0 - S_7$, respectively, are transferred to the system microprocessor 22, which preferably can calculate the locations and correct values of up to four 10-bit symbol errors under firmware control.

Whether calculated by the GF-ALU 44, or by the system microprocessor 22, the corrected data location(s) and value(s), respectively, are substituted for the erroneous data value(s) by the system microprocessor 22, while the retrieved data block is still retained in the holding buffer 28. Because the location(s) and correct value(s), respectively, are calculated based on the 10-

bit symbol format, the system microprocessor 22 translates the 10-bit location(s) and value(s) into the corresponding 16-bit location(s) and value(s), before substitution in the data block. The data block is then released from the holding buffer 28 to the host interface circuit 14 and host system 10, respectively, for use in its intended application.

Referring to FIG. 5, the state controller 42 serially invokes each new GF-ALU instruction 45 to the GF-ALU 44. A 10-bit symbol contained either in one of registers, $R_0 \dots R_7$, 46a-h, respectively, or comprising a particular error syndrome, $S_0 \dots S_7$, respectively, is used as the input value for the operation indicated in the GF-ALU instruction 45. The possible 10-bit arithmetic operations, i.e. over a Galois field $GF(2^{10})$, or "GF(1024)," include addition 52, which is preferably carried out by X'OR operation, multiplication 54, inversion 56, and squaring 58, respectively, as indicated in the particular state instruction. A $y^2 + y + C$ solution table look-up function 60 is also provided in the GF-ALU 44, for finding the quadratic solution(s) in the Galois field $GF(2^{10})$ for a given value of C in the double error decoding process.

After each instruction, the GF-ALU output 49 is loaded into one of registers, $R_0 \dots R_7$, 46a-h, respectively, which is readied by a destination address 47 sent by the register load enables 48. The GF-ALU output 49 is occasionally checked for a zero or non-zero

value by a zero detect circuit 62, in order to verify whether a particular single or double error solution attempt has succeeded or failed, respectively. If either a zero or non-zero value is detected, depending upon the particular state, a status bit or "flag" 66 is sent to the state controller 42, which will set the appropriate status, e.g. "decoder fails," or "successful double/single error decoding," to alert the system microprocessor 22 to obtain the requisite information from either the syndrome generator (if "decoder fails") or the appropriate registers $R_4 - R_7$, 46e-h, respectively. In certain state operations, the failure to locate a viable solution in the look-up table 60 will also trigger a status flag 66 to be sent.

In accordance with one aspect of the present invention, the operations of the GF-ALU 44 are preferably substantially hardware-minimized by employing 5-bit extension field operations over a Galois field $GF(2^5)$, or $GF(32)$, to assist in performing certain of the 10-bit arithmetic operations. In the illustrated preferred embodiment, the 5-bit extension field operation units include 5-bit multipliers 55, and inverters 57, respectively.

In the 5-bit operations, each 5-bit nibble or "number" is treated in a standard basis as a fourth degree polynomial, i.e., where each 5-bit number, $\{d_4, d_3, d_2, d_1, d_0\}$, is represented as coefficients in the fourth degree polynomial, $d_4x^4 + d_3x^3 + d_2x^2 + d_1x + d_0x^0$. The Galois field $GF(2^5)$, or $GF(32)$, which is defined by an

arbitrarily selected first element and a fifth degree generator polynomial, designated herein as " $p(x)$," is preferably generated based on the irreducible polynomial $x^5 + x^2 + 1$. Its first element α^1 (i.e., excluding α^0), is selected to be equal to x , where x represents the binary field element in polynomial representation over $GF(2)$, as is known in the art. The 31 possible non-zero field elements are represented by the successive powers of alpha, including α^0 . Accordingly, each successive element in the field may be determined by multiplying the preceding field element by α^1 , mod $p(x)$. Put another way, the non-zero field elements are represented by the antilogs of the powers of α from 0 to 31, where each of the antilog values are calculated mod $p(x)$, so that no antilog value can exceed 31, with α^{31} mapping back to α^0 , (i.e., $\alpha^{31} = \alpha^0 = 1$). For example:

$$\begin{aligned}
 \alpha^1 &= x^1 \bmod p(x) = 2^1 = (\text{binary}) 00010; \\
 \alpha^2 &= \alpha^1 \cdot \alpha^1 \bmod p(x) = x^1 \cdot x^1 \bmod p(x) = x^2 = 00100; \\
 \alpha^3 &= \alpha^2 \cdot \alpha^1 \bmod p(x) = 01000; \\
 \alpha^4 &= \alpha^3 \cdot \alpha^1 \bmod p(x) = 10000; \\
 \alpha^5 &= \alpha^4 \cdot \alpha^1 = x^4 \cdot x^1 \bmod p(x) = x^5 \bmod (x^5 + x^2 + 1) = \\
 &\hspace{15em} x^2 + 1 = 00101 \text{ (etc.)}.
 \end{aligned}$$

After the $GF(32)$ antilog table is calculated, generating a log table ("base α ") is simply a matter of reversing the antilog table by mapping each power of alpha with its corresponding antilog value. Hardware multipliers, inverters and adders for $GF(32)$ with

$\alpha^1 = x$ and $p(x) = x^5 + x^2 + 1$ over $GF(2)$, are maintained within the GF-ALU 44 to facilitate the 5-bit extension field operations. To facilitate further explanation of the 5-bit extension field operations, the antilog and log tables (decimal) for $GF(2^5)$ are set forth in Tables 4 and 5:

TABLE 4. Antilog Table/Elements of $GF(2^5)$.

i	α^i	i	α^i
0	1	16	27
1	2	17	19
2	4	18	3
3	8	19	6
4	16	20	12
5	5	21	24
6	10	22	21
7	20	23	15
8	13	24	30
9	26	25	25
10	17	26	23
11	7	27	11
12	14	28	22
13	28	29	9
14	29	30	18
15	31	31	1

TABLE 5. Log Table for GF(2⁵)

i	LOG[i]	i	LOG[i]
1	0/31	17	10
2	1	18	30
3	18	19	17
4	2	20	7
5	5	21	22
6	19	22	28
7	11	23	26
8	3	24	21
9	29	25	25
10	6	26	9
11	27	27	16
12	20	28	13
13	8	29	14
14	12	30	24
15	23	31	15
16	4		

Preferably, the system microprocessor 22 is also provided with the appropriate Galois field logs and antilogs to facilitate calculations for the three and four error correction routines.

Once the results for GF(2⁵) are determined, the 10-bit

multiplication and inversion operations may be easily performed by 5-bit "extension field" operations. In particular, according to another aspect of the present invention, the 10 bit numbers are represented in a standard basis as a sum of powers of "y" over GF(2⁵), with each 10-bit symbol treated as two 5-bit nibbles or "numbers," (e₀, e₁), which represent e₁y + e₀, to perform the requisite multiplication and inversion functions. Preferably, the multiplication of the 10-bit numbers is performed as standard polynomial multiplication, reduced by mod P₁₀₂₄(y), where P(y) is the irreducible polynomial: P₁₀₂₄(y) = y² + y + 1, over GF(2⁵).

By way of example, let m₀ = 0101110100 and m₁ = 1001101111. A 10-bit multiply of m₀ * m₁ is required. According to this aspect of the invention, it is carried out as follows:

$$\begin{aligned}
 m_0 &= \{01011\}y + \{10100\}; \\
 m_1 &= \{10011\}y + \{01111\}. \\
 \text{Letting } \{01011\} &= a \text{ (= (11)dec);} \\
 \{10100\} &= b \text{ (= (20)dec);} \\
 \{10011\} &= c \text{ (= (19)dec); and} \\
 \{01111\} &= d \text{ (= (15)dec);} \\
 m_0 * m_1 &= (ay + b)(cy + d) = acy^2 + (bc + ad)y + bd. \\
 (acy^2 + (bc + ad)y + bd) \bmod (y^2 + y + 1) &= \\
 &= (ac + bc + ad)y + (bd + ac).
 \end{aligned}$$

Each of the two 5-bit products, (i.e., ac, bc, ad, bd), may be determined by referring to the previously generated antilog and log

(base α) tables, as follows:

$ac = \text{antilog}_\alpha[(\log_\alpha a + \log_\alpha c) \bmod (31)]$
 $\quad = \text{antilog}[(27 + 17) \bmod (31)]$
 $\quad = \text{antilog}[13] = 28.$
5 $bc = \text{antilog}_\alpha[(\log_\alpha b + \log_\alpha c) \bmod (31)]$
 $\quad = \text{antilog}[(7 + 17) \bmod (31)]$
 $\quad = \text{antilog}[24] = 30.$
 $bd = \text{antilog}_\alpha[(\log_\alpha b + \log_\alpha d) \bmod (31)]$
 $\quad = \text{antilog}[(7 + 23) \bmod (31)]$
10 $\quad = \text{antilog}[30] = 18.$
 $ad = \text{antilog}_\alpha[(\log_\alpha a + \log_\alpha d) \bmod (31)]$
 $\quad = \text{antilog}[(27 + 23) \bmod (31)]$
 $\quad = \text{antilog}[19] = 6.$

15 Addition of the five bit products is performed by standard XOR
operation:

$(ac + bc + ad) = \{11100\} + \{11110\} + \{00110\} = \{00100\};$ and
 $(bd + ac) = \{10010\} + \{11100\} = \{01110\}.$

Concatenating the two results, $m_0 * m_1 = \{0010001110\}.$

20 To ensure full disclosure of the aforescribed preferred
embodiment, a corresponding verilog listing of the error correction
module 36 is provided as follows:

```

module decoder(
    constclk,    /* positive edge byte clock */
    decstart,    /* start of decoding */
    resetn,      /* decoder negative reset */
    5    syrs0000, /* syndrome 0 */
    syrs0001,    /* syndrome 1 */
    syrs0002,    /* syndrome 2 */
    syrs0003,    /* syndrome 3 */
    syrs0004,    /* syndrome 4 */
    10    syrs0005, /* syndrome 5 */
    syrs0006,    /* syndrome 6 */
    syrs0007,    /* syndrome 7 */
    locater0,    /* locator of first error */
    locater1,    /* locator of 2nd error */
    15    errvalu0, /* value of first error */
    errvalu1,    /* value of 2nd error */
    decrstat,    /* decoder status flags */
    finished     /* status indicating finished */
);

20    input    constclk;
    input    decstart;
    input    resetn;
    input [9:0] syrs0000;

```

```

    input  [9:0]  syrs0001;
    input  [9:0]  syrs0002;
    input  [9:0]  syrs0003;
    input  [9:0]  syrs0004;
5   input  [9:0]  syrs0005;
    input  [9:0]  syrs0006;
    input  [9:0]  syrs0007;
    output [9:0]  locater0;
    output [9:0]  locater1;
10  output [9:0]  errvalu0;
    output [9:0]  errvalu1;
    output [9:0]  decrstat;
    output [1:0]  finished;

    // synopsys state_vector st8
15  parameter [6:0] /* synopsys enum bus_states */
        st_00 = 7'h00, st_01 = 7'h01, st_02 = 7'h02, st_03 = 7'h03,
        st_04 = 7'h04, st_05 = 7'h05, st_06 = 7'h06, st_07 = 7'h07,
        st_08 = 7'h08, st_09 = 7'h09, st_0a = 7'h0a, st_0b = 7'h0b,
        st_0c = 7'h0c, st_0d = 7'h0d, st_0e = 7'h0e, st_0f = 7'h0f,
20  st_10 = 7'h10, st_11 = 7'h11, st_12 = 7'h12, st_13 = 7'h13,
        st_14 = 7'h14, st_15 = 7'h15, st_16 = 7'h16, st_17 = 7'h17,
        st_18 = 7'h18, st_19 = 7'h19, st_1a = 7'h1a, st_1b = 7'h1b,
        st_1c = 7'h1c, st_1d = 7'h1d, st_1e = 7'h1e, st_1f = 7'h1f,

```

st_20 = 7'h20, st_21 = 7'h21, st_22 = 7'h22, st_23 = 7'h23,
 st_24 = 7'h24, st_25 = 7'h25, st_26 = 7'h26, st_27 = 7'h27,
 st_28 = 7'h28, st_29 = 7'h29, st_2a = 7'h2a, st_2b = 7'h2b,
 st_2c = 7'h2c, st_2d = 7'h2d, st_2e = 7'h2e, st_2f = 7'h2f,
 5 st_30 = 7'h30, st_31 = 7'h31, st_32 = 7'h32, st_33 = 7'h33,
 st_34 = 7'h34, st_35 = 7'h35, st_36 = 7'h36, st_37 = 7'h37,
 st_38 = 7'h38, st_39 = 7'h39, st_3a = 7'h3a, st_3b = 7'h3b,
 st_3c = 7'h3c, st_3d = 7'h3d, st_3e = 7'h3e, st_3f = 7'h3f,
 st_40 = 7'h40, st_41 = 7'h41, st_42 = 7'h42, st_43 = 7'h43,
 10 st_44 = 7'h44, st_45 = 7'h45, st_46 = 7'h46, st_47 = 7'h47,
 st_48 = 7'h48, st_49 = 7'h49, st_4a = 7'h4a, st_4b = 7'h4b,
 st_4c = 7'h4c, st_4d = 7'h4d, st_4e = 7'h4e, st_4f = 7'h4f,
 st_50 = 7'h50, st_51 = 7'h51, st_52 = 7'h52, st_53 = 7'h53,
 st_54 = 7'h54, st_55 = 7'h55, st_56 = 7'h56, st_57 = 7'h57,
 15 st_58 = 7'h58, st_59 = 7'h59, st_5a = 7'h5a, st_5b = 7'h5b,
 st_5c = 7'h5c, st_5d = 7'h5d, st_5e = 7'h5e, st_5f = 7'h5f,
 st_60 = 7'h60, st_61 = 7'h61, st_62 = 7'h62, st_63 = 7'h63,
 st_64 = 7'h64, st_65 = 7'h65, st_66 = 7'h66, st_67 = 7'h67,
 st_68 = 7'h68, st_69 = 7'h69, st_6a = 7'h6a, st_6b = 7'h6b,
 20 st_6c = 7'h6c, st_6d = 7'h6d, st_6e = 7'h6e, st_6f = 7'h6f,
 st_70 = 7'h70, st_71 = 7'h71, st_72 = 7'h72, st_73 = 7'h73,
 st_74 = 7'h74, st_75 = 7'h75, st_76 = 7'h76, st_77 = 7'h77,
 st_78 = 7'h78, st_79 = 7'h79, st_7a = 7'h7a, st_7b = 7'h7b,
 st_7c = 7'h7c, st_7d = 7'h7d, st_7e = 7'h7e, st_7f = 7'h7f;

```

reg    [6:0] /*synopsys enum bus_states */ st8, nxst8;

parameter [3:0]
    i_r0 = 4'd0, i_r1 = 4'd1, i_r2 = 4'd2, i_r3 = 4'd3,
    i_r4 = 4'd4, i_r5 = 4'd5, i_r6 = 4'd6, i_r7 = 4'd7,
5    i_s0 = 4'h8, i_s1 = 4'h9, i_s2 = 4'ha, i_s3 = 4'hb,
    i_s4 = 4'hc, i_s5 = 4'hd, i_s6 = 4'h3, i_s7 = 4'hf;

parameter [2:0]
    load = 3'd0, accm = 3'd1, mult = 3'd2, invt = 3'd3,
    dbls = 3'd4, sqre = 3'd5, stat = 3'd6, noop = 3'd7,
10    o_r0 = 3'd0, o_r1 = 3'd1, o_r2 = 3'd2, o_r3 = 3'd3,
    o_r4 = 3'd4, o_r5 = 3'd5, o_r6 = 3'd6, o_r7 = 3'd7;

reg [10:0] fnk;

wire [1:0] decrstat;

wire [3:0] sourcadd;
15 wire [2:0] instruct;
wire [2:0] destnadd;

wire    finished;

wire    bz;

wire    nz;
20 wire    instatus;

```



```

    assign bz = instatus;
    assign nz = ~bz;

    assign sourcadd = fnk {10:7};
    assign instruct = fnk {6:4};
5   assign destnadd = fnk {3:1};
    assign finished = fnk {9};

    always @(st8 or bz or nz)
        case (st8) // synopsys full_case parallel_case

            st_00:begin nxst8=st_01; fnk={i_s0,load,o_r1,1'd0}; end // S0          into R1 multiplier
10   st_01:begin nxst8=st_02; fnk={i_s2,mult,o_r0,1'd0}; end // S0S2          into R0 accumulator
            st_02:begin nxst8=st_03; fnk={i_s1, sqre,o_r2,1'd0}; end // S1*2      into R2
            st_03:begin nxst8=st_04; fnk={4'h2,accm,o_r2,1'd0}; end // S0S2 + S1**2 into R2

            /* R2 now contains det[M2] */
            /* det[M2] is nonzero if there are two or more errors */
15   /* det[M2] is zero if there are one or more than 2 errors */

            st_04:begin nxst8=({7{bz}}&st_4e)|({7{nz}}&st_05); fnk={4'h3,load,o_r3,1'd0}; end // noop branch
            st_05:begin nxst8=st_06; fnk={i_s3,mult,o_r0,1'd0}; end // S0S3          into R0
            accumulator
            st_06:begin nxst8=st_07; fnk={i_s1,load,o_r1,1'd0}; end // S1          into R1

```

```

multiplier

st_07:begin nxst8=st_08; fnk={i_s2,mult,o_r3,1'd0}; end // S1S2           into R3
st_08:begin nxst8=st_09; fnk={4'h3,accm,o_r3,1'd0}; end // S1S2 + SOS3   into R3

/* R3 is the numerator of Lambda1                                     */
5  /* R3 is zero causes the two error solution to fail               */

st_09:begin nxst8=({7{bz}}&st_66)|({7{nz}}&st_0a); fnk={4'h3,load,o_r3,1'd0}; end // noop branch
st_0a:begin nxst8=st_0b; fnk={i_s3,mult,o_r0,1'd0}; end // S1S3           into R0
accumulator

st_0b:begin nxst8=st_0c; fnk={i_s2,sqre,o_r4,1'd0}; end // S2**2           into R4
10 st_0c:begin nxst8=st_0d; fnk={4'h4,accm,o_r4,1'd0}; end // S2**2 + S1S3   into R4

/* R4 is the numerator of Lambda2                                     */
/* R4 is zero causes the two error solution to fail               */

st_0d:begin nxst8=({7{bz}}&st_66)|({7{nz}}&st_0e); fnk={4'h4,load,o_r4,1'd0}; end // nop branch
st_0e:begin nxst8=st_0f; fnk={4'h2,invnt,o_r1,1'd0}; end // inverse{det[M2]} into R1
15 multiplie

st_0f:begin nxst8=st_10; fnk={4'h3,mult,o_r3,1'd0}; end // Lambda1         into R3
st_10:begin nxst8=st_11; fnk={4'h4,mult,o_r4,1'd0}; end // Lambda2         into R4

/* now we have equation of the form z**2 + Lambda2 == 0 to solve */

```

```

st_11:begin nxst8 = st_12; fnk = {4'h3, invt, o_r1, 1'd0}; end // 1/Lambda1          into R1
multiplie

st_12:begin nxst8 = st_13; fnk = {i_s1, mult, o_r7, 1'd0}; end // S1/Lambda1      into R7
st_13:begin nxst8 = st_14; fnk = {4'h1, sqre, o_r1, 1'd0}; end // 1/(Lambda1**2) into R1
5 multiplie

st_14:begin nxst8 = st_15; fnk = {4'h4, mult, o_r1, 1'd0}; end // Lambda2/(Lambda1**2) into R1
multiplie

/* now we have equation of the form y**2 + y + c = 0 to solve */
/* where c = Lambda2/(Lambda1**2) */
10 /* if one solution exists, we call it w */

st_15:begin nxst8 = st_16; fnk = {4'h1, db1s, o_r1, 1'd0}; end // w into R1 multiplier

/* no such solution causes the two error solution to fail */

st_16:begin nxst8 = ({7bz})&st_66|({7{nz})&st_17); fnk = {4'h1, load, o_r1, 1'd0}; end // noop branch
st_17:begin nxst8 = st_18; fnk = {4'h3, mult, o_r4, 1'd0}; end // Lambda1 w = X0 into R4
15 st_18:begin nxst8 = st_19; fnk = {4'h4, load, o_r0, 1'd0}; end // X0 into R0 accumulator
st_19:begin nxst8 = st_1a; fnk = {4'h3, accm, o_r5, 1'd0}; end // Lambda1 + X0 = X1 into R5

/* now we have the error locaters done, find error values */

```

```

st_1a:begin nxst8=st_1b; fnk={i_s0,mult,o_r0,1'd0}; end // S0 w
                                                    into R0
st_1b:begin nxst8=st_1c; fnk={4'h7,accm,o_r0,1'd0}; end // S0 w + S1/Lambda1 = Y1 into R0

/* a zero error value causes the two error solution to fail */

st_1c:begin nxst8=({7{bz}}&st_66)|({7{nz}}&st_1d); fnk={4'h0,load,o_r0,1'd0}; end // noop branch
5 st_1d:begin nxst8=st_1e; fnk={i_s0,accm,o_r6,1'd0}; end // S0 + Y1 = Y0
                                                    into 46

/* zero error value causes the two error solution to fail */

st_1e:begin nxst8=({7{bz}}&st_66)|({7{nz}}&st_1f); fnk={4'h'6,load,o_r6,1'd0}; end // noop branch
st_1f:begin nxst8=st_20; fnk={4'h0,load,o_r7,1'd0}; end // Y1 moved to standard place, R7

/* double error solution is now complete (R4, R5, R6, R7) = {X0, X1, Y0, Y1} */
10 /* check the solution against all syndromes:
*/

st_20:begin nxst8=st_21; fnk={4'h4,sqre,o_r1,1'd0}; end // X0**2
                                                    into R1
multiplie

st_21:begin nxst8=st_22; fnk={4'h6,mult,o_r2,1'd0}; end // X0**2 Y0
                                                    into R2
st_22:begin nxst8=st_23; fnk={4'h5,sqre,o_r1,1'd0}; end // X1**2
                                                    into R1
15 multiplie

st_23:begin nxst8=st_24; fnk={4'h7,mult,o_r3,1'd0}; end // X1**2 Y1
                                                    into R3
st_24:begin nxst8=st_25; fnk={4'h3,load,o_r0,1'd0}; end // X1**2 Y1
                                                    into R0
accumulat

```

```

st_25:begin nxst8=st_26; fnk={4'h2,accm,o_r0,1'd0}; end //  $X1 \ll 2 Y1 + X0 \ll 2 Y0$  into R0
accumulat

st_26:begin nxst8=st_27; fnk={i_s2,accm,o_r0,1'd0}; end //  $S2 + X1 \ll 2 Y1 + X0 \ll 2 Y0$  into R0

/* a nonzero value causes the two error solution to fail */

5 st_27:begin nxst8=({7{nz}}&st_66)|({7{bz}}&st_28); fnk=4'h0,load,o_r0,1'd0; end // noop branch
st_28:begin nxst8=st_29; fnk={4'h4,load,o_r1,1'd0}; end // X0 into R1
multiplie

st_29:begin nxst8=st_2a; fnk={4'h2,mult,o_r2,1'd0}; end //  $X0 \ll 3 Y0$  into R2
st_2a:begin nxst8=st_2b; fnk={4'h5,load,o_r1,1'd0}; end // X1 into R1
10 multiplie

st_2b:begin nxst8=st_2c; fnk={4'h3,mult,o_r3,1'd0}; end //  $X1 \ll 3 Y1$  into R3
st_2c:begin nxst8=st_2d; fnk={4'h3,load,o_r0,1'd0}; end //  $X1 \ll 3 Y1$  into R0
accumulat

st_2d:begin nxst8=st_2e; fnk={4'h2,addm,o_r0,1'd0}; end //  $X1 \ll 3 Y1 + X0 \ll 3 Y0$  into R0
15 accumulat

st_2e:begin nxst8=st_2f; fnk={i_s3,accm,o_r0,1'd0}; end //  $S3 + X1 \ll 3 Y1 + X0 \ll 3 Y0$  into R0

/* a nonzero value causes the two error solution to fail */

st_2f:begin nxst8=({7nz}}&st_66)|({7{bz}}&st_30); fnk=4'h0,load,o_r0,1'd0; end // noop branch
st_30:begin nxst8=st_31; fnk={4'h3,mult,o_r3,1'd0}; end //  $X1 \ll 4 Y1$  into R3
20 st_31:begin nxst8=st_32; fnk={4'h4,load,o_r1,1'd0}; end // X0 into R1

```

```

multiplie

st_32:begin nxst8=st_33; fnk={4'h2,mult,o_r2,1'd0}; end // X0**4 Y0          into R2
st_33:begin nxst8=st_34; fnk={4'h3,load,o_r0,1'd0}; end // X1**4 Y1          into R0
accumulat
5  st_34:begin nxst8=st_35; fnk={4'h2,accm,o_r0,1'd0}; end // X1**4 Y1 + X0**4 Y0  into R0
accumulat
st_35:begin nxst8=st_36; fnk={i_s4,accm,o_r0,1'd0}; end // S4 + X1**4 Y1 + X0**4 Y0 into R0

/* a nonzero value causes the two error solution to fail */

st_36:begin nxst8=({7{nz}}&st_66|({7{bz}}&st_37); fnk={4'h0,load,o_r0,1'd0}; end // noop branch
10 st_37:begin nxst8=st_38; fnk={4'h2,mult,o_r2,1'd0}; end // X0**5 Y0          into R2
st_38:begin nxst8=st_39; fnk={4'h5,load,o_r1,1'd0}; end // X1          into R1
multiple
st_39:begin nxst8=st_3a; fnk={4'h3,mult,o_r3,1'd0}; end // X1**5 Y1          into R3
st_3a:begin nxst8=st_3b; fnk={4'h3,load,o_r0,1'd0}; end // X1**5 Y1          into R0
15 accumulat
st_3b:begin nxst8=st_3c; fnk={4'h2,accm,o_r0,1'd0}; end // X1**5 Y1 + X0**5 Y0  into R0
accumulat
st_3c:begin nxst8=st_3d; fnk={i_s5,accm,o_r0,1'd0}; end // S5 + X1**5 Y1 + X0**5 Y0 into R0

/* a nonzero value causes th two error solution to fail */

20 st_3d:begin nxst8=({7nz}}&st_66|({7{bz}}&st_3e); fnk={4'h0,load,o_r0,1'd0}; end // noop branch

```

```

st_3e:begin nxst8=st_3f; fnk={4'h3,mult,o_r3,1'd0}; end // X1**6 Y1          into R3
st_3f:begin nxst8=st_40; fnk={4'h4,load,o_r1,1'd0}; end // X0              into R1
multiplie
st_40:begin nxst8=st_41; fnk={4'h2,mult,o_r2,1'd0}; end // X0**6 Y0          into R2
5  st_41:begin nxst8=st_42; fnk={4'h3,load,o_r0,1'd0}; end // X1**6 Y1          into R0
accumulat
st_42:begin nxst8=st_43; fnk={4'h2,accm,o_r0,1'd0}; end // X1**6 Y1 + X0**6 Y0 into R0
accumulat
st_43:begin nxst8=st_44; fnk={i_s6,accm,o_r0,1'd0}; end // S6 + X1**6 Y1 + X0**6 Y0 into Ro

10  /* a nonzero value causes the tow error solution to fail */

st_44:begin nxst8=({7{nz}}&st_66)|({7{bz}}&st_45); fnk={4'h0,load,o_r0,1'd0}; end // noop branch
st_45:begin nxst8=st_46; fnk={4'h2,mult,o_r2,1'd0}; end // X0**7 Y0          into R2
st_46:begin nxst8=st_47; fnk={4'h5,load,o_r1,1'd0}; end // X1              into R1
multiplie
15  st_47:begin nxst8=st_48; fnk={4'h3,mult,o_r3,1'd0}; end // X1**7 Y1          into R3
st_48:begin nxst8=st_49; fnk={4'h3,load,o_r0,1'd0}; end // X1**7 Y1          into R0
accumulat
st_49:begin nxst8=st_4a; fnk={4'h2,accm,o_r0,1'd0}; end // X1~*7 Y1 + X0**7 Y0 into R0
accumulat
20  st_4a:begin nxst8=st_4b; fnk={i_s7,accm,o_r0,1'd0}; end // S7 + X1**7 Y1 + X0**7 Y0 into R0

/* a nonzero value causes the two error solution to fail */

```

```

st_4b:begin nxst8 = ({7{nz}} & st_66) ({7{bz}} & st_4c); fnk = {4'h0, load, o_r0, 1'd0}; end // noop branch
st_4c:begin nxst8 = st_4d; fnk = {4'h2, stat, o_r2, 1'd0}; end // set status register to 2 errors
st_4d:begin nxst8 = st_69; fnk = {4'h2, load, o_r2, 1'd0}; end // noop unconditional branch

/* start single error decoding */

5  st_4e:begin nxst8 = st_4f; fnk = {i_s0, invt, o_r1, 1'd0}; end // 1/S0          into R1
    multiplie

/* a zero value causes the single error solution to fail */

st_4f:begin nxst8 = ({7{bz}} & st_66) ({7{nz}} & st_50); fnk = {4'h1, load, o_r1, 1'd0}; end // noop branch
st_50:begin nxst8 = st_51; fnk = {i_s1, mult, o_r1, 1'd0}; end // S1/S0 = X0          into R1
10 multiplie

/* a zero value causes the single error solution to fail */

st_51:begin nxst8 = ({7{bz}} & st_66) ({7{nz}} & st_52); fnk = {4'h1, load, o_r1, 1'd0}; end // noop branch
st_52:begin nxst8 = st_53; fnk = {i_s1, mult, o_r0, 1'd0}; end // S1 X0          into R0
    accumulat

15 st_53:begin nxst8 = st_54; fnk = {i_s2, accm, o_r0, 1'd0}; end // S1 X0 + S2          into R0
    accumulat

/* a nonzero value causes the single error solution to fail */

```



```

st_54:begin nxst8 = ({7{nz}}&st_66)|({7{nz}}&st_55); fnk = {4'h1,load,o_r1,1'd0}; end // noop branch
st_55:begin nxst8 = st_56; fnk = {i_s2,mult,o_r0,1'd0}; end // S2 X0                      into R0
accumulat
st_56:begin nxst8 = st_57; fnk = {i_s3,accm,o_r0,1'd0}; end // S2 X0 + S3              into R0
5  accumulat

/* a nonzero value causes the single error solution to fail */

st_57:begin nxst8 = ({7{nz}}&st_66)|({7{bz}}&st_58); fnk = {4'h1,load,o_r1,1'd0}; end // noop branch
st_58:begin nxst8 = st_59; fnk = {i_s3,mult,o_r0,1'd0}; end // S3 X0                      into R0
accumulat
10 st_59:begin nxst8 = st_5a; fnk = {i_s4,accm,o_r0,1'd0}; end // S3 X0 + S4              into R0
accumulat

/* a nonzero value causes the single error solution to fail */

st_5a:begin nxst8 = ({7{nz}}&st_66)|({7{bz}}&st_5b); fnk = {4'h1,load,o_r1,1'd0}; end // noop branch
st_5b:begin nxst8 = st_5c; fnk = {i_s4,mult,o_r0,1'd0}; end // S4 X0                      into R0
15 accumulat
st_5c:begin nxst8 = st_5d; fnk = {i_s5,accm,o_r0,1'd0}; end // S4 X0 + S5              into R0
accumulat

/* a nonzero value causes the single error solution to fail */

```

```

st_5d:begin nxst8 = ({7{nz}}&st_66|({7{bz}}&st_5e); fnk = {4'h1,load,o_r1,1'd0}; end // noop branch
st_5e:begin nxst8 = st_5f; fnk = {i_s5,mult,o_r0,1'd0}; end // S5 X0                      into R0
accumulat
st_5f:begin nxst8 = st_60; fnk = {i_s6,accm,o_r0,1'd0}; end // S5 X0 + S6                      into R0
5  accumulat

/* a nonzero value causes the single error solution to fail */

st_60:begin nxst8 = ({7{nz}}&st_66|({7{bz}}&st_61); fnk = {4'h1,load,o_r1,1'd0}; end // noop branch
st_61:begin nxst8 = st_62; fnk = {i_s6,mult,o_r0,1'd0}; end // S6 X0                      into R0
accumulat
10 st_62:begin nxst8 = st_63; fnk = {s7,accm,o_r0,1'd0}; end // S6 X0 + S7                      into R0
accumulat

/* a nonzero value causes the single error solution to fail */

st_63:begin nxst8 = ({7{nz}}&st_66|({7{bz}}&st_64); fnk = {4'h1,load,o_r1,1'd0}; end // noop branch
st_64:begin nxst8 = st_65; fnk = {4'h1,stat,o_r1,1'd0}; end // set status register to 1 error
15 st_65:begin nxst8 = st_67; fnk = {4'h1,load,o_r1,1'd0}; end // noop unconditional branch

st_66:begin nxst8 = st_69; fnk = {4'h0,stat,o_r0,1'd0}; end // decoder failure: set status to 0
st_67:begin nxst8 = st_68; fnk = {i_r1,load,o_r4,1'd0}; end // load r1 value into r4 locator output
st_68:begin nxst8 = st_69; fnk = {i_s0,load,o_r6,1'd0}; end // load S0 value into r4 locator output
st_69:begin nxst8 = st_69; fnk = {4'h0,load,o_r0,1'd1}; end // decoder complete

```

```
        endcase

        always @ (posedge constclk or negedge resetn)
        begin
            if (!resetn)
                st8 <= st_69;
            else if (finished && decstart)
                st8 <= 7'd0;
            else
                st8 <= nxst8;
        end

        gf_alu my1stalu(
            .resetn (resetn),
            .syrs0000(syrs0000),
            .syrs0001(syrs0001),
            .syrs0002(syrs0002),
            .syrs0003(syrs0003),
            .syrs0004(syrs0004),
            .syrs0005(syrs0005),
            .syrs0006(syrs0006),
            .syrs0007(syrs0007),
            .locater0(locater0),
            .locater1(locater1),
```

```

        .errvalu0(errvalu0),
        .errvalu1(errvalu1),
        .decodclk(constclk),
        .instruct(instruct),
5      .sourcadd(sourcadd),
        .destnadd(destnadd),
        .decrstat(decrstat),
        .instatus(instatus);

    endmodule

10  module gf_alu (syrs0000, /* syndrome 0 */
        syrs0001, /* syndrome 1 */
        syrs0002, /* syndrome 2 */
        syrs0003, /* syndrome 3 */
        syrs0004, /* syndrome 4 */
15      syrs0005, /* syndrome 5 */
        syrs0006, /* syndrome 6 */
        syrs0007, /* syndrome 7 */
        locater0, /* register 4 of ALU */
        locater1, /* register 5 of ALU */
20      errvalu0, /* register 6 of ALU */
        errvalu1, /* register 7 of ALU */
        decodclk, /* alu positive edge clock 20 Mhz */
        instruct, /* instruction to be executed */

```

```

        sourcadd, /* address of source operand      */
        destnadd, /* address of destination operand */
        decrstat, /* status of decoder          */
        instatus  /* status of completed instruction */
    );

    input      resetn;

    input [9:0] syrs0000;
    input [9:0] syrs0001;
    input [9:0] syrs0002;
10    input [9:0] syrs0003;
    input [9:0] syrs0004;
    input [9:0] syrs0005;
    input [9:0] syrs0006;
    input [9:0] syrs0007;
15    input      decodclk;
    input [2:0] instruct;
    input [3:0] sourcadd;
    input [2:0] destnadd;

    output [9:0] locater0;
20    output [9:0] locater1;
    output [9:0] errvalu0;
    output [9:0] errvalu1;
    output [1:0] decrstat;

```

```

output      instatus;

//reg      instatus;
reg [9:0] workreg0;
reg [1:0] decrstat;
5 reg [9:0] workreg1;
reg [9:0] workreg2;
reg [9:0] workreg3;
reg [9:0] workreg4;
reg [9:0] workreg5;
10 reg [9:0] workreg6;
reg [9:0] workreg7;
reg      instatus;
reg [9:0] sourcer;
reg [9:0] aluout;
15 reg      status;

// instruction 0 destination <= source
wire [9:0] accumul; // instruction 1 destination <= sourcer accumulated w output 0
wire [9:0] product; // instruction 2 destination <= sourcer multiplied by output 1
wire [9:0] inverse; // instruction 3 destination <= inverse of sourcer
20 wire [9:0] dblsoln; // instruction 4 destination <= soln of ( $y^{**2} + y + \text{sourcer} = 0$ )
wire [9:0] squared; // instruction 5 destination <=  $\text{sourcer}^{**2}$ 
// instruction 6 no operation

```

```

// instruction 7 no operation

wire iszero;
wire noroot;
wire statenab;
5  wire [7:0] regenab;

assign locater0 = workreg4;
assign locater1 = workreg5;
assign errvalu0 = workreg6;
assign errvalu1 = workreg7;

10  /* get source operand */

always @(sourcadd or
       workreg0 or workreg1 or workreg2 or workreg3 or
       workreg4 or workreg5 or workreg6 or workreg7 or
       syrs0000 or syrs0001 or syrs0002 or syrs0003 or
15  syrs0004 or syrs0005 or syrs0006 or syrs0007)
begin
    case (sourcadd)
        4'd0 : sourcer = workreg0;
        4'd1 : sourcer = workreg1;
        4'd2 : sourcer = workreg2;
20  4'd3 : sourcer = workreg3;

```

```

4'd4 : sourcer = workreg4;
4'd5 : sourcer = workreg5;
4'd6 : sourcer = workreg6;
4'd7 : sourcer = workreg7;
5 4'd8 : sourcer = syrs0000;
4'd9 : sourcer = syrs0001;
4'd10 : sourcer = syrs0002;
4'd11 : sourcer = syrs0003;
4'd12 : sourcer = syrs0004;
10 4'd13 : sourcer = syrs0005;
4'd14 : sourcer = syrs0006;
4'd15 : sourcer = syrs0007;

endcase

end

15 /* computation units */

assign      accumul = workreg0 ^ sourcer;
multiply    decmultr(.x(workreg1), .y(sourcer), .z(product));
inverse      decinvrt(.y(sourcer), .z(inverse));
dbltrbl     dectable(.c(sourcer), .y(dblsoln), .noroot));
20 squarer   decsquar(.x(sourcer), .z(squared));

/* assign alu output and status */

```



```
always @(instruct or
    sourcer or
    accumul or
    product or
5    inverse or
    dblsoln or
    squared or
    noroot or
    iszero)
10    begin
        case (instruct)
            3'd0 : begin aluout = sourcer; status = iszero; end
            3'd1 : begin aluout = accumul; status = iszero; end
            3'd2 : begin aluout = product; status = iszero; end
15            3'd3 : begin aluout = inverse; status = iszero; end
            3'd4 : begin aluout = dblsoln; status = noroot; end
            3'd5 : begin aluout = squared; status = iszero; end
            3'd6 : begin aluout = sourcer; status = 1'd0; end
            3'd7 : begin aluout = 9'd0; status = 1'd0; end
20        endcase
    end

/* assign iszero as zero output of alu */
```

```

    assign iszero = ~(aluout);

    /* assign output register enables */

    assign statenab      = (instruct == 3'd6);

    assign regenab[0] = (destnadd == 3'd0);
5    assign regenab[1] = (destnadd == 3'd1);
    assign regenab[2] = (destnadd == 3'd2);
    assign regenab[3] = (destnadd == 3'd3);
    assign regenab[4] = (destnadd == 3'd4);
    assign regenab[5] = (destnadd == 3'd5);
10    assign regenab[6] = (destnadd == 3'd6);
    assign regenab[7] = (destnadd == 3'd7);

    /* update outputisters */

    always @ (posedge decodclk)
        begin
15        //Note: add reset for workreg0 only, since a known value is
        //needed here during initialization.
        if (resetn == 0)
            workreg0 <= 10'h000;
        else

```

```

workreg0 <= ({10{regenab[0]}} & aluout | ({10{~regenab[0]}} & workreg0);
workreg1 <= ({10{regenab[1]}} & aluout | ({10{~regenab[1]}} & workreg1);
workreg2 <= ({10{regenab[2]}} & aluout | ({10{~regenab[2]}} & workreg2);
workreg3 <= ({10{regenab[3]}} & aluout | ({10{~regenab[3]}} & workreg3);
5 workreg4 <= ({10{regenab[4]}} & aluout | ({10{~regenab[4]}} & workreg4);
workreg5 <= ({10{regenab[5]}} & aluout | ({10{~regenab[5]}} & workreg5);
workreg6 <= ({10{regenab[6]}} & aluout | ({10{~regenab[6]}} & workreg6);
workreg7 <= ({10{regenab[7]}} & aluout | ({10{~regenab[7]}} & workreg7);
instatus <= status;

10 if (statenab)
    decrstat <= sourcadd[1:0];
    end

endmodule

module multiply (x, y, z); // galois field multiplier of x and y to get z

15 input [9:0] x;
input [9:0] y;
input [9:0] z;

wire [4:0] 1sb0;
wire [4:0] msb0;

```

```
    wire [4:0] 1sb1;
    wire [4:0] msb1;
    wire [4:0] msb0msb1;
    wire [4:0] 1sb01sb1;
5    wire [4:0] msb01sb1;
    wire [4:0] msb11sb0;
    wire [4:0] p0m0m1;
    wire [4:0] p1m0m1;

    assign 1sb0 = x[4:0];
10    assign 1sb1 = y[4:0];
    assign msb0 = x[9:5];
    assign msb1 = y[9:5];

    gatemul5 subm0( .x(1sb0), .y(1sb1), .z(1sb01sb1));
    gatemul5 subm1( .x(msb0), .y(msb1), .z(msb0msb1));
15    gatemul5 subm2( .x(1sb0), .y(msb1), .z(1sb11sb0));
    gatemul5 subm4( .x(msb0), .y(1sb1), .z(msb01sb1));
    assign p0m0m1 = msb0msb1;
    assign p1m0m1 = msb0msb1;

    assign z[4:0] = 1sb01sb1 ^ p0m0m1;
20    assign z[9:5] = msb01sb1 ^ msb11sb0 ^ p1m0m1;
```

```

endmodule

module gatemul5(x, y, z); // galois field multiplier of x and y to get z

input  [4:0] x;
input  [4:0] y;
5   input  [4:0] zx;

wire [4:0] alpha0x;
wire [4:0] alpha1x;
wire [4:0] alpha2x;
wire [4:0] alpha3x;
10  wire [4:0] alpha4x;

assign alpha0x = x;
assign alpha1x = {alpha0x[3:0],1'b0} ^ ({5{alpha0x[4]}} & 5'd5);
assign alpha2x = {alpha1x[3:0],1'b0} ^ ({5{alpha1x[4]}} & 5'd5);
assign alpha3x = {alpha2x[3:0],1'b0} ^ ({5{alpha2x[4]}} & 5'd5);
15 assign alpha4x = {alpha3x[3:0],1'b0} ^ ({5{alpha3x[4]}} & 5'd5);

assign z[0] =
    (alpha0x[0] & y[0]) ^
    (alpha1x[0] & y[1]) ^
    (alpha2x[0] & y[2]) ^

```

```
(alpha3x[0] & y[3]) ^  
(alpha4x[0] & y[4]);  
  
assign z[1] =  
    (alpha0x[1] & y[0]) ^  
5    (alpha1x[1] & y[1]) ^  
    (alpha2x[1] & y[2]) ^  
    (alpha3x[1] & y[3]) ^  
    (alpha4x[1] & y[4]);  
  
assign z[2] =  
  
10    (alpha0x[2] & y[0]) ^  
    (alpha1x[2] & y[1]) ^  
    (alpha2x[2] & y[2]) ^  
    (alpha3x[2] & y[3]) ^  
    (alpha4x[2] & y[4]);  
  
15    assign z[3] =  
        (alpha0x[3] & y[0]) ^  
        (alpha1x[3] & y[1]) ^  
        (alpha2x[3] & y[2]) ^  
        (alpha3x[3] & y[3]) ^  
20    (alpha4x[3] & y[4]);
```

```

    assign z[4] =
        (alpha0x[4] & y[0]) ^
        (alpha1x[4] & y[1]) ^
        (alpha2x[4] & y[2]) ^
5      (alpha3x[4] & y[3]) ^
        (alpha4x[4] & y[4]);

    endmodule

    module squarer(x, z);
    input  [9:0] x;
10   output [9:0] z;
    assign z =    ({10{x[0]}} & 10'd1)      ^
                  ({10{x[1]}} & 10'd4)      ^
                  ({10{x[2]}} & 10'd16)     ^
                  ({10{x[3]}} & 10'd10)     ^
15   ({10{x[4]}} & 10'd13)      ^
                  ({10{x[5]}} & 10'd33)     ^
                  ({10{x[6]}} & 10'd132)    ^
                  ({10{x[7]}} & 10'd528)    ^
                  ({10{x[8]}} & 10'd330)    ^
20   ({10{x[9]}} & 10'd429)      ^
    endmodule

```

```
module inverse (y, z); // galois field inverter of y to get z

input [9:0] y;
input [9:0] z;

wire [4:0] 1sb;
5 wire [4:0] msb;
wire [4:0] 1sb1sb;
wire [4:0] msbmsb;
wire [4:0] 1sbmsb;
wire [4:0] p1msb;
10 wire [4:0] denom;
wire [4:0] numer;
wire [4:0] p0msbmsb;
wire [4:0] p11sbmsb;
wire [4:0] 1it1inv;

15 assign 1sb = y[4:0];
assign msb = y[9:5];

gatemul5 subm0(.x(1sb), .y(1sb), .z(1sb01sb));
gatemul5 subm1(.x(msb), .y(msb), .z(msbmsb));
assign p1msb = msb;
```



```
    gatemul5 subm4( .x(p1msb), .y(1sb), .z(p11sbmsb));
    assign p0msbmsb = msbmsb;

    assign number = 1sb ^p1msb;
    assign denom = 1sb1sb ^ p0msbmsb ^p11sbmsb;

5    gf32inv inv0(.x(denom), .z(lit1inv));

    gatemul5 subm5( .x(lit1inv), .y(number), .z([4:0]));
    gatemul5 subm6( .x(lit1inv), .y(msb), .z(z[9:5]));

    endmodule

    module gf32inv(x, z);
10    input  [4:0] x;
        output      [4:0] z;
        reg  [4:0] z;
        always @(x)
            begin
15                case (x)
                    5,b00000 : z = 5'b00000;
                    5,b00001 : z = 5'b00001;
                    5,b00010 : z = 5'b10010;
                    5,b00011 : z = 5'b11100;
```

5,b00100 : z = 5'b01001;
5,b00101 : z = 5'b10111;
5,b00110 : z = 5'b01110;
5,b00111 : z = 5'b01100;
5 5,b01000 : z = 5'b10110;
5,b01001 : z = 5'b00100;
5,b01010 : z = 5'b11001;
5,b01011 : z = 5'b10000;
5,b01100 : z = 5'b00111;
10 5,b01101 : z = 5'b01111;
5,b01110 : z = 5'b00110;
5,b01111 : z = 5'b01101;
5,b10000 : z = 5'b01011;
5,b10001 : z = 5'b11000;
15 5,b10010 : z = 5'b00010;
5,b10011 : z = 5'b11101;
5,b10100 : z = 5'b11110;
5,b10101 : z = 5'b11010;
5,b10110 : z = 5'b01000;
20 5,b10111 : z = 5'b00101;
5,b11000 : z = 5'b10001;
5,b11001 : z = 5'b01010;
5,b11010 : z = 5'b10101;
5,b11011 : z = 5'b11111;

```

        5,b11100 : z = 5'b00011;
        5,b11101 : z = 5'b10011;
        5,b11110 : z = 5'b10100;
        5,b11111 : z = 5'b11011;
5      endcase
      end
    endmodule

module dbltrbl (c, y, noroot);
input  [9:0] c;
10  output [9:0] y;
    output  noroot;
    assign noroot = c[8] ^ c[5];
    assign y[90]  = 1'd0
    assign y[1]   = c[7] ^ c[4] ^ c[2];
15  assign y[2]   = c[7] ^ c[6] ^ c[4] ^ c[3];
    assign y[3]   = c[9] ^ c[6] ^ c[4] ^ c[2] ^ c[1];
    assign y[7]   = c[9] ^ c[5];
    assign y[9]   = c[5];
    assign y[6]   = c[9] ^ c[7];
20  assign y[8]   = y[6] ^ c[6];
    assign y[4]   = y[6] ^ c[6] ^ c[5] ^ c[3];
    assign y[5]   = y[8] ^ c[3] ^ c[0];
endmodule

```

Thus, an error correction methodology and system architecture for implementing a 10-bit Reed-Solomon code has been disclosed. While the foregoing detailed description was directed to a semiconductor based data storage and retrieval system, it will be
5 apparent to those skilled in the art that the described error correction methodology and architecture can be effectively practiced with any digital data storage system, e.g., such as magnetic or optical based memory systems, as well as with any system involving the handling, transfer, and/or storage of blocks
10 of digital data between elements thereof, including digital communications systems, where the correction of data being transmitted or stored is required. While the present invention is particularly well suited for systems and architectures encountering non-bursty, substantially random data errors, it may be equally
15 employed in those systems and architectures encountering bursty error patterns, as well.

Thus, it would be apparent to those skilled in the art that many more modifications are possible without departing from the inventive concepts herein. The invention, therefore is not to be
20 restricted except in the spirit of the appended claims.

What is claimed is:

- 1 1. A data storage and retrieval system for receiving,
2 storing and retrieving, respectively, digital data packetized in
3 blocks of k m -bit data symbols, comprising:
4 means for reformatting the blocks of m -bit data symbols into
5 blocks of 10-bit data symbols;
6 an encoder having means for generating r 10-bit error check
7 symbols from each reformatted block of 10-bit data symbols;
8 means for reformatting said r 10-bit error check symbols
9 generated by said encoder into $(10/m)*r$ m -bit error check symbols;
10 means for appending said $(10/m)*r$ m -bit error check symbols to
11 the respective m -bit data block from which they were generated; and
12 data storage means for receiving and storing, respectively,
13 said m -bit data blocks, including the respective appended $(10/m)*r$
14 m -bit error check symbols.
- 1 2. The data storage and retrieval system of claim 1, further
2 comprising means for retrieving said stored m -bit data blocks from
3 said data storage means and reformatting them into respective 10-
4 bit code words, each retrieved 10-bit code word comprising k 10-bit
5 data symbols and r 10-bit error check symbols.

1 3. The data storage and retrieval system of claim 2, further
2 comprising
3 a syndrome generator for generating r 10-bit error syndromes
4 from each retrieved 10-bit code word;
5 means for detecting the existence of at least one non-zero
6 error syndrome in a given set of generated error syndromes; and
7 error correction circuitry comprising:
8 means for receiving said r 10-bit error syndromes from said
9 syndrome generator when at least one non-zero syndrome is detected,
10 a dedicated Galois field arithmetic logic unit
11 having means for executing arithmetic operations on 10-
12 bit symbols by performing extension field operations over
13 a Galois field of 2^j ,
14 a programmed controller for providing state
15 instructions to said arithmetic logic unit which carry
16 out a programmed error correction routine for determining
17 the location of, and correction value for, respectively,
18 up to 2 erroneous 10-bit data symbols in a given
19 retrieved 10-bit code word.

1 4. The data storage and retrieval system of claim 3, said
2 dedicated Galois field arithmetic logic unit utilizing a Galois
3 field $GF(2^j)$ generated from the irreducible polynomial $g(x) = x^j +$
4 $x^2 + 1$, over $GF(2)$.

1 5. The data storage and retrieval system of claim 4, said
2 dedicated Galois field arithmetic logic unit further generating the
3 Galois field $GF(2^{10})$ from the irreducible polynomial $P_{1024}(y) = y^2 +$
4 $y + 1$, over $GF(2^4)$.

1 6. The data storage and retrieval system of claim 5, said
2 Galois field $GF(2^{10})$ having as its primitive element $(101)_h$.

1 7. The data storage and retrieval system of claim 3, said
2 data storage means characterized in that data errors occurring in
3 a block of data stored therein occur in substantially random bit
4 locations.

1 8. The data storage and retrieval system of claim 3, said
2 data storage means comprising a semiconductor based memory.

1 9. The data storage and retrieval system of claim 8, said
2 semiconductor based memory comprising a FLASH random access memory.

1 10. The data storage and retrieval system of claim 3, said
2 encoder combined with said syndrome generator in a single circuit.

1 11. A data storage and retrieval system for receiving,
2 storing and retrieving, respectively, data packetized in blocks of
3 m-bit data symbols, comprising:
4 an interface circuit for receiving the blocks of m-bit data
5 symbols from an external data processing system;
6 a first buffer for temporarily storing the blocks of m-bit
7 data symbols from said interface circuit;
8 means for reformatting said blocks of m-bit data symbols
9 received from said interface circuit into blocks of k 10-bit data
10 symbols;
11 an encoder circuit having means for generating r 10-bit error
12 check symbols from each block of k 10-bit data symbols;
13 means for reformatting said r 10-bit error check symbols
14 generated by said encoder into $(10/m)*r$ m-bit error check symbols,
15 wherein said $(10/m)*r$ m-bit error check symbols are appended in
16 said first buffer to the respective m-bit data block from which
17 they were generated;
18 data storage means for receiving and storing, respectively,
19 said m-bit data blocks, including the respective appended m-bit
20 error check symbols from said first buffer;
21 means for retrieving said stored m-bit data blocks from said
22 data storage means and reformatting them into respective 10-bit
23 code words, each retrieved 10-bit code word comprising k 10-bit
24 data symbols and r 10-bit error check symbols;

25 a syndrome generator for generating r 10-bit error syndromes
26 from each retrieved 10-bit code word;
27 means for detecting the existence of at least one non-zero
28 error syndrome; and
29 error correction circuitry comprising:
30 means for receiving said r 10-bit error syndromes
31 from said syndrome generator when at least one non-zero
32 syndrome is detected,
33 a dedicated Galois field arithmetic logic unit
34 having means for executing arithmetic operations on 10-
35 bit symbols by performing extension field operations over
36 a Galois field of 2^5 ,
37 a programmed controller for providing state
38 instructions to said arithmetic logic unit which carry
39 out a programmed error correction routine for determining
40 the location of, and correction value for, respectively,
41 up to 2 erroneous 10-bit data symbols in a given
42 retrieved 10-bit code word.

1 12. The data storage and retrieval system of claim 11, said
2 dedicated Galois field arithmetic logic unit utilizing a Galois
3 field $GF(2^5)$ generated from the irreducible polynomial $g(x) = x^5 +$
4 $x^2 + 1$, over $GF(2)$.

1 13. The data storage and retrieval system of claim 12, said
2 dedicated Galois field arithmetic logic unit further generating the
3 Galois field $GF(2^{10})$ from the irreducible polynomial $P_{1024}(y) = y^2 +$
4 $y + 1$, over $GF(2^5)$, and having as its primitive element $(101)h$.

1 14. The data storage and retrieval system of claim 11,
2 further comprising a second buffer for receiving and temporarily
3 storing, respectively, said retrieved m-bit data blocks from said
4 data storage means.

1 15. The data storage and retrieval system of claim 11,
2 wherein $r = 8$.

1 16. The data storage and retrieval system of claim 11,
2 wherein $(10/m)*k = 256$, $m = 16$, and $r = 8$, respectively.

1 17. The data storage and retrieval system of claim 11,
2 wherein $(10/m)*k = 512$, $m = 8$, and $r = 8$, respectively.

1 18. In a data processing system, error correction apparatus
2 for detecting and correcting data errors, comprising:
3 means for receiving r 10-bit error syndromes generated from a
4 10-bit Reed Solomon code word;
5 a dedicated Galois field arithmetic logic unit having means
6 for executing an error correction algorithm by performing
7 arithmetic operations on 10-bit symbols;
8 a programmed controller for providing state instructions to
9 said arithmetic logic unit which carry out said error correction
10 algorithm.

1 19. The error correction apparatus set forth in claim 18,
2 said dedicated Galois field arithmetic logic unit generating a
3 Galois field $GF(2^{10})$ using the irreducible polynomial $P_{1024}(y) = y^2 +$
4 $y + 1$, over a Galois field 2^5 , said Galois field 2^5 being generated
5 using the irreducible polynomial $g(x) = x^5 + x^2 + 1$, over $GF(2)$.

1 20. The data processing system in claim 18, further
2 comprising a semiconductor based digital data storage and retrieval
3 sub-system.

1 21. In a data processing system, error correction apparatus
2 for detecting and correcting data errors, comprising:
3 an arithmetic logic unit having means for executing an error
4 correction algorithm on 10-bit error syndromes, said arithmetic
5 logic unit utilizing a Galois field $GF(2^5)$ generated from the
6 irreducible polynomial $g(x) = x^5 + x^2 + 1$, over $GF(2)$; and
7 a programmed controller for providing state instructions to
8 said arithmetic logic unit which carry out said error correction
9 algorithm.

1 22. The data storage and retrieval system of claim 21, said
2 arithmetic logic unit further utilizing a a Galois field $GF(2^{10})$
3 generated from the irreducible polynomial $P_{1024}(y) = y^2 + y + 1$, over
4 $GF(2^5)$.

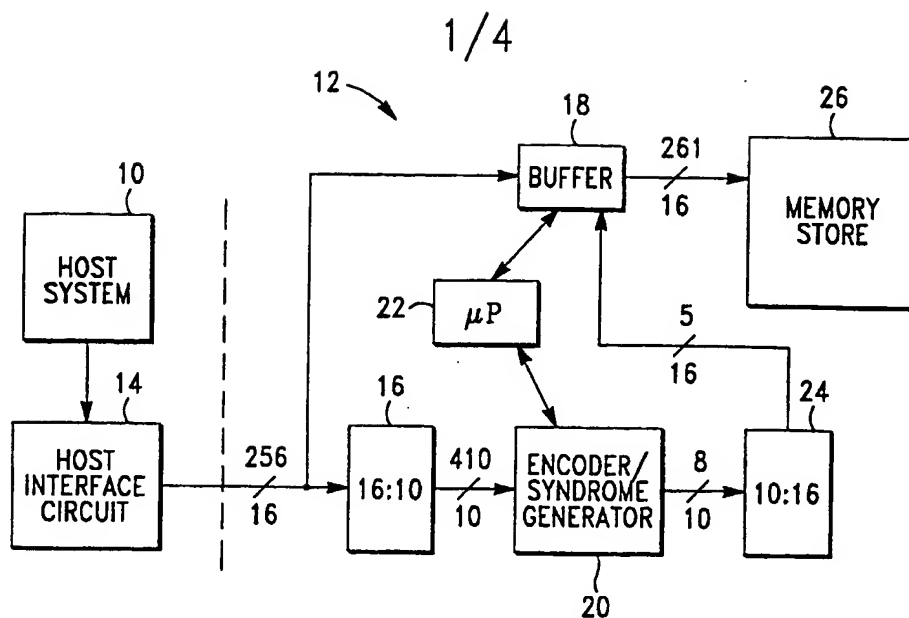


FIG.-1

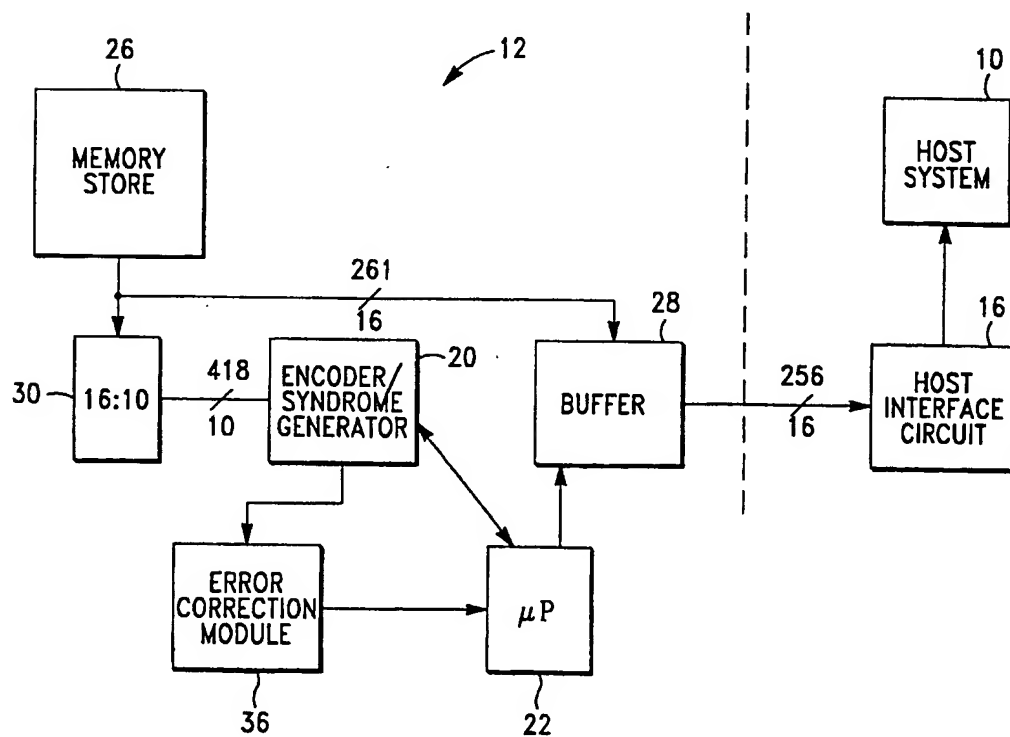


FIG.-2

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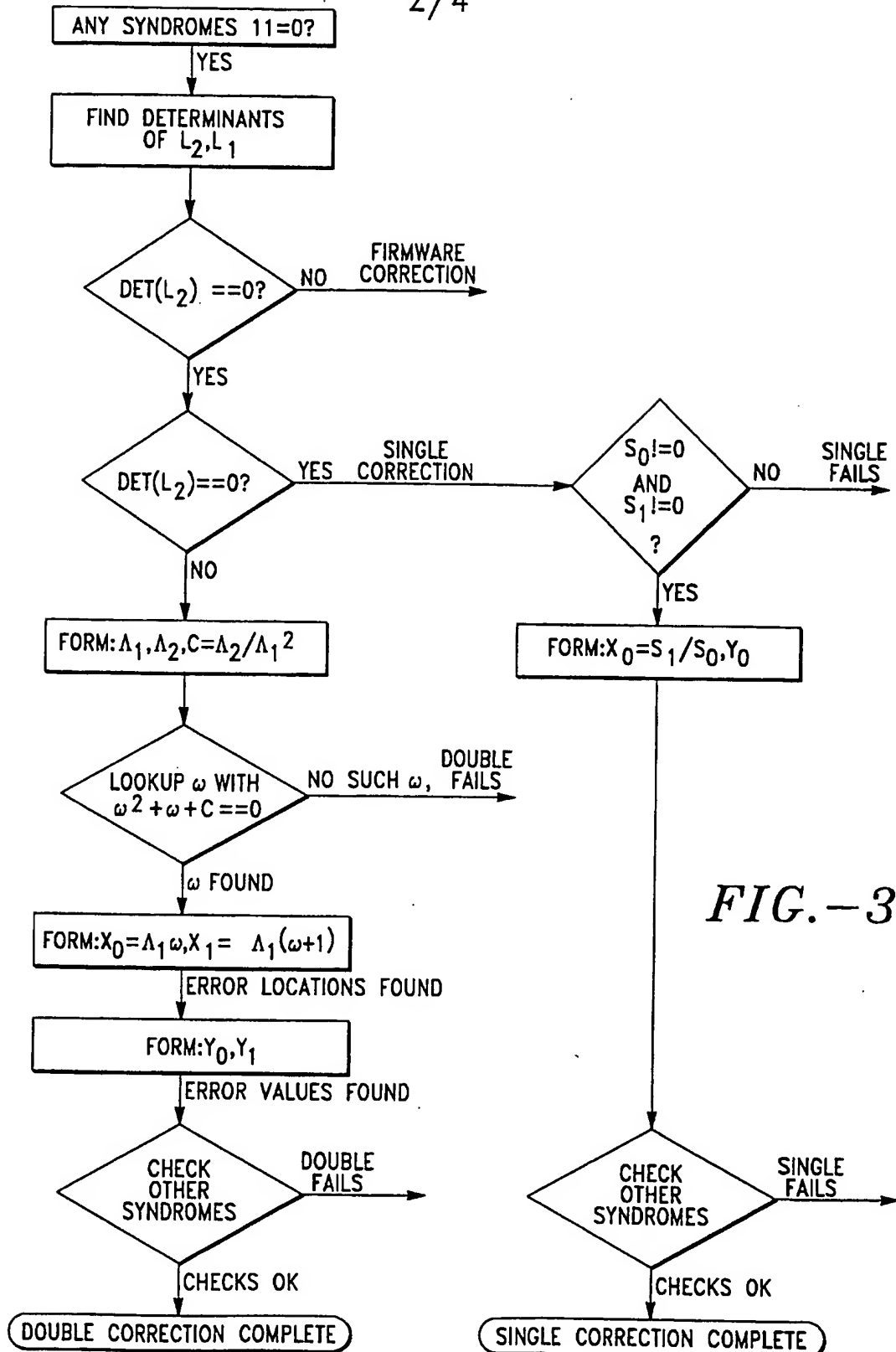


FIG. -3

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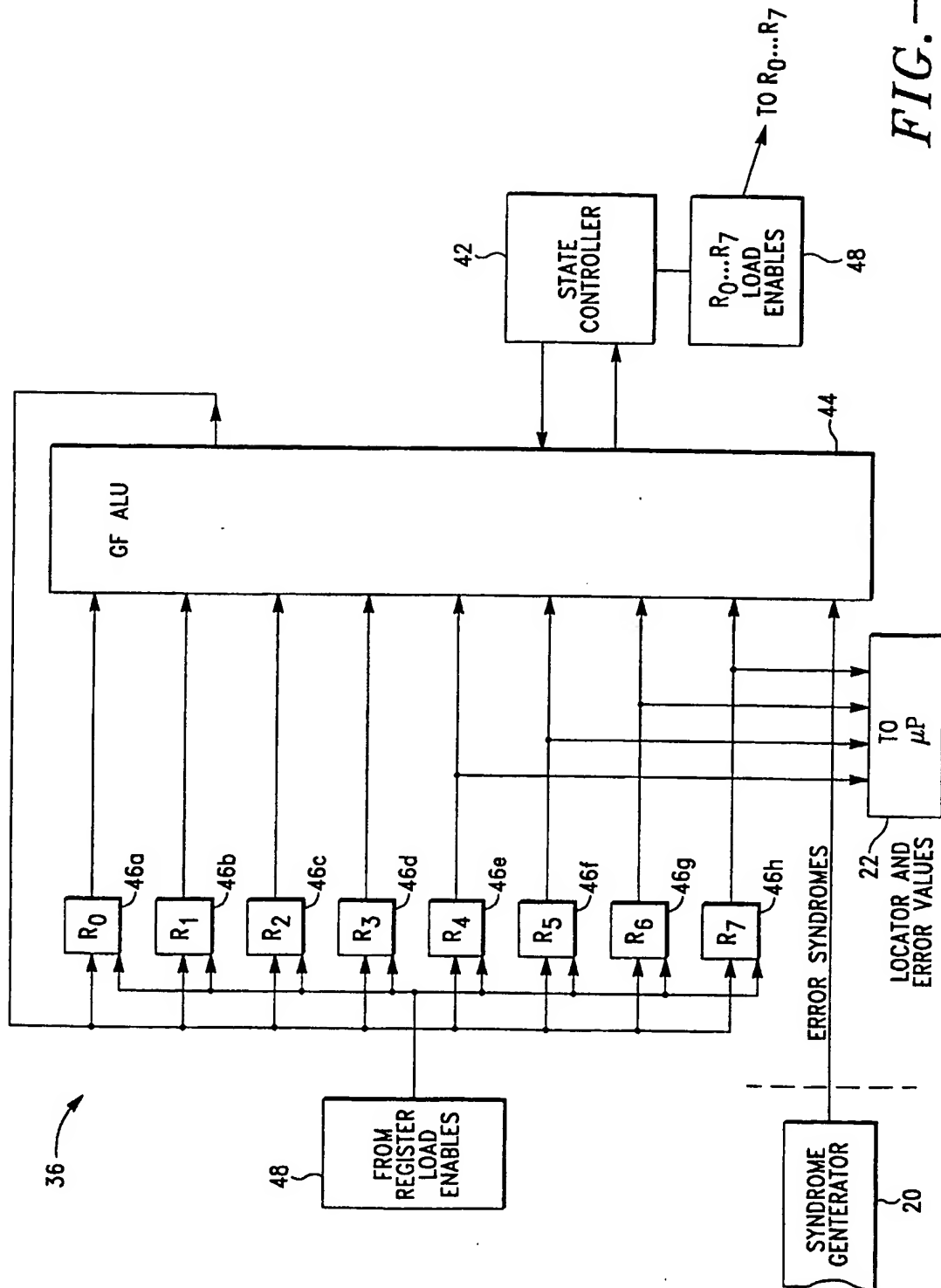


FIG. 4

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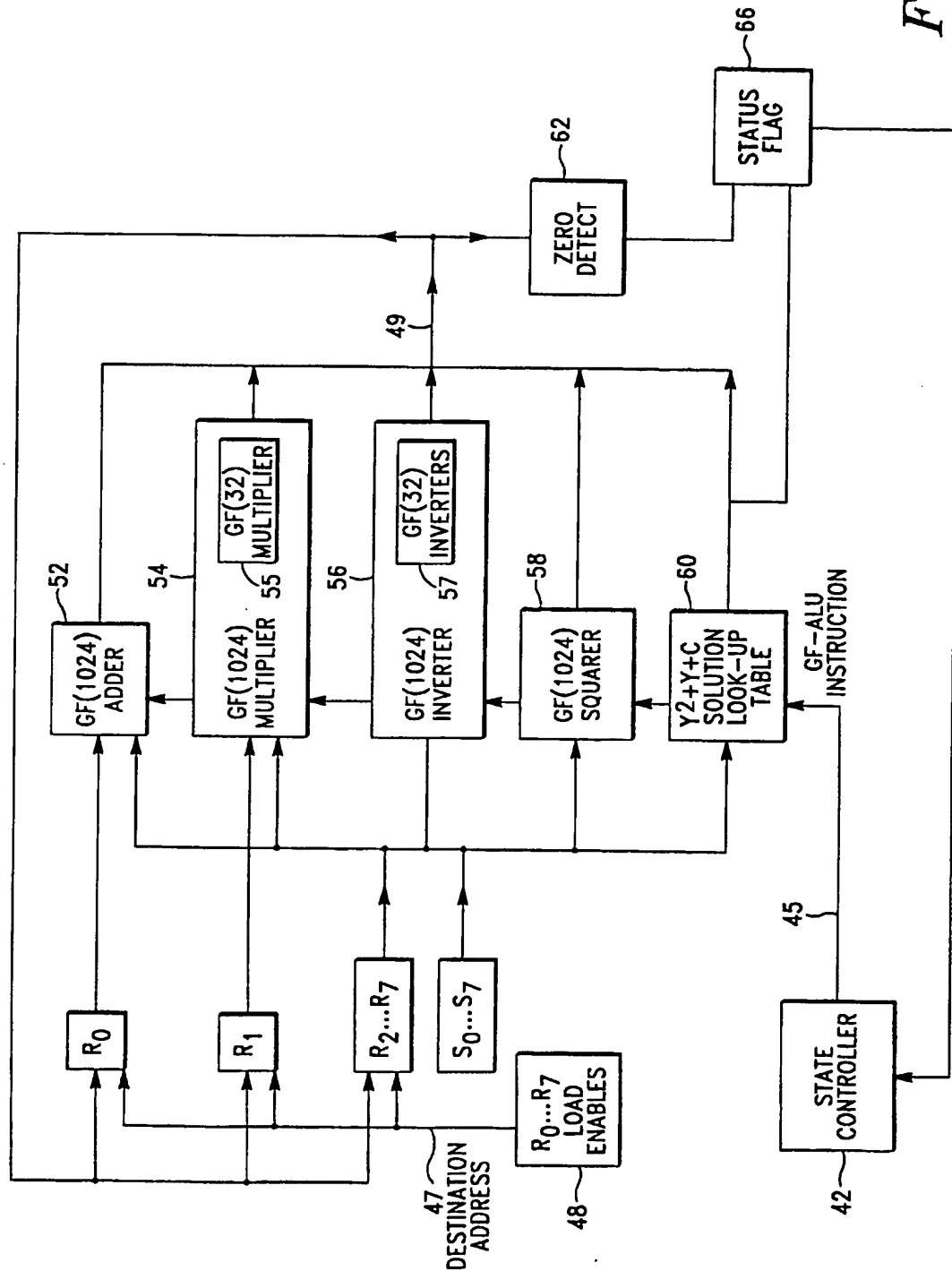


FIG.-5

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US96/10074

A. CLASSIFICATION OF SUBJECT MATTER																				
IPC(6) : H03M 13/00; G11C 29/00																				
US CL : 371/37.1, 37.5, 38.1, 39.1, 40.1																				
According to International Patent Classification (IPC) or to both national classification and IPC																				
B. FIELDS SEARCHED																				
Minimum documentation searched (classification system followed by classification symbols)																				
U.S. : 371/37.1, 37.2, 37.5, 38.1, 39.1, 40.1																				
Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched																				
Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)																				
APS: (10 bit#)/ab																				
C. DOCUMENTS CONSIDERED TO BE RELEVANT																				
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.																		
Y	US, A, 4,730,321 (MACHADO), 08 March 1988, see abstract, column 7, line 34 - column 8, line 47.	1-22																		
Y	US, A, 4,856,003 (WENG) 08 August 1989, see abstract.	1-22																		
A	US, A, 5,241,546 (PETERSON et al.) 31 August 1993, see abstract.	1-22																		
A	US, A, 4,364,081 (HASIMOTO et al.) 14 December 1982, see abstract.	1-22																		
A	US, A, 4,413,339 (RIGGLE ET AL.) 01 November 1983, see Fig. 2 and abstract.	1-22																		
<input checked="" type="checkbox"/> Further documents are listed in the continuation of Box C. <input type="checkbox"/> See patent family annex.																				
<table border="0"> <tr> <td>* Special categories of cited documents:</td> <td>*T</td> <td>later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention</td> </tr> <tr> <td>*A* document defining the general state of the art which is not considered to be part of particular relevance</td> <td>*X*</td> <td>document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone</td> </tr> <tr> <td>*E* earlier document published on or after the international filing date</td> <td>*Y*</td> <td>document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art</td> </tr> <tr> <td>*L* document which may throw doubt on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)</td> <td>*Z*</td> <td>document member of the same patent family</td> </tr> <tr> <td>*O* document referring to an oral disclosure, use, exhibition or other means</td> <td></td> <td></td> </tr> <tr> <td>*P* document published prior to the international filing date but later than the priority date claimed</td> <td></td> <td></td> </tr> </table>			* Special categories of cited documents:	*T	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention	*A* document defining the general state of the art which is not considered to be part of particular relevance	*X*	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone	*E* earlier document published on or after the international filing date	*Y*	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art	*L* document which may throw doubt on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	*Z*	document member of the same patent family	*O* document referring to an oral disclosure, use, exhibition or other means			*P* document published prior to the international filing date but later than the priority date claimed		
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Date of the actual completion of the international search		Date of mailing of the international search report																		
31 JULY 1996		05.09.96																		
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		Telephone No. (703) 305-9706																		

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US96/10074

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	IEEE, (0-7803-0593-0) 1992, Fettweis et al., "A Combined Reed-Solomon Encoder and Syndrome Generator with Small Hardware Complexity", pages 1871-1874.	1-22